Studies on Drying Characteristics of Some Crops in a Portable Tapered Fluidized Bed Dryer and Its Design Optimization

Thesis Submitted By

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CERTIFICATE

This is to certify that the thesis entitled "**Studies on Drying Characteristics of Some Crops in a Portable Tapered Fluidized Bed Dryer and Its Design optimization**" submitted by **Ms. Subasini Jena** (Roll No. **511CH106**) to National Institute of Technology, Rourkela towards partial fulfillment of the requirements for the award of the ***Doctor of Philosophy*** degree in Chemical Engineering, is a bonafide record of her work carried out under my supervision and guidance.

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ABSTRACT

The drying characteristics for different crops (grains and vegetables) are analyzed using a fluidized bed dryer with respect to the moisture content, diffusivity and physical properties of grains and vegetables. Temperature dependence of mass transfer coefficients is established in terms of Arrhenius type of relation. Drying constant and shrinkage constant of different shaped samples are also studied. Simple mathematical expressions are developed relating volumetric shrinkage constant with drying constant. Dimensionless groups viz. Reynolds number, Schmidt number, and Sherwood number are determined at different drying conditions. With the knowledge of diffusivity and dimensionless groups, mass transfer coefficients are determined. The physical properties of samples are also analyzed at different levels of moisture contents. The performance of fluidized bed dryer measured in terms of its efficiency is investigated by using different samples. The effects of different system parameters (viz. temperature, time, and density of material and fluid velocity) on the drying performances i.e. on moisture content, diffusivity and efficiency of the samples are also studied through different mathematical expressions.

Artificial Neural Network and Taguchi analysis are used to validate the developed correlations for drying characteristics. The chi square (χ^2), correlation coefficient (R^2) and root mean square error (RMSE) findings indicate that ANN and Taguchi analysis optimize the system parameters of the fluidized bed drying more effectively than regression analysis. Thus the developed correlations can be used for parameter-optimizations over a wide range thereby providing a better platform for efficient operations. Again a portable tapered fluidized bed dryer is designed to provide drying in turn storing opportunity to farmers. Thus the present work lays foundation for an efficient dryer to be designed effectively which can further be scaled up suitably for industrial applications.

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CHAPTER I

INTRODUCTION

1.1. General introduction to drying

The standard of living in a rural community depends upon the range of crops grown, the capacity to grow in quantity and also upon the facilities for efficient handling, drying, storage and marketing of crops [1]. Crop losses are a major problem in many regions, and are increasing due to climate change and food security issues. However, careful and simple preservation and storage techniques can help reduce crop losses. Proper drying is considered as the biggest single factor in determining whether grain will be effectively stored without damage.

All grain contains moisture. The problem is keeping the amount of water in the grain at a very low level. If the grain is wet then the seed coat is not strong enough to keep out insects and moulds which cause spoilage. Also, if the grain is wet it will respirate much faster. This will increase the temperature of the grain. Insects and moulds like warm grain. The grain kernels could even germinate inside the storage place once they are warm and wet enough.

Drying is a method of preserving food. Drying reduces the water activity, thereby preserving foods by avoiding microbial growth and deteriorative chemical reactions. The drying process aims at a reduction of the moisture content in most products, to guarantee their consistency in storage and transport. The main purposes of drying are to increase shelf life, reduce packaging and storage costs, lower shipping weights, improve sensory attributes, encapsulate flavours, and preserve nutritional value in some cases. For storage purposes, the moisture content of materials must fall within a acceptable range so that they do not undergo any type of degradation or alterations in quality or appearance. To achieve the desired moisture content, the material must be dried [1].

It is well known by experienced farmers that dry grain stores much better and safer than grain which is wet. Therefore it is very essential to carry out detailed studies on grain drying.

Drying is the process of the removal of water (moisture) from hygroscopic materials at low to medium moisture contents (normally <30% wet basis) using evaporation. When the moisture content of the agricultural products is high (usually >50% wet basis) the process of removal of moisture is referred to as dehydration. Drying/dehydration is one of the most important post-harvest treatments being adopted worldwide to reduce the spoilage and increase the shelf life or storage durability of agricultural products. Removal of moisture is a complex simultaneous heat and mass transfer process but treating it as such is not sufficient because end use characteristics or quality of the product cannot be handled this way.

Dehydration operations are necessary steps in the chemical and food processing industries. The basic objective in drying food products is the removal of water in the solids up to a certain level, at which microbial spoilage and deteriorative chemical reactions are greatly minimized. The wide variety of dehydrated foods, which today are available to the consumer (snacks, dry mixes and soups, dried fruits, etc.) and the interesting concern for meeting quality specifications and energy conservation, emphasize the need for a thorough understanding of the drying process.

1.2. General introduction to fluidized bed technology

Fluidized bed technology is widely used in a variety of solid handling systems of which drying is one. In general fluid bed drying is used wherever gentle handling conditions are required and close control is needed or, wherever small driving forces must be utilized. Fluidized bed drying applications include drying of such materials as polystyrene, sodium chromate, sodium dichromate, ammonium nitrate prills, urea nitrate prills, mixed fertilizers, ammonium phosphate, polyethylene polymers, and inorganic salts, etc. Although fluidization is an extremely versatile process, applying it to the greatest advantage requires a clear understanding of its principles and recognition of its limitations. Consideration of the mechanism of fluidization and drying in combination leads to very interesting observations. In the fluidized bed, the solid particles are in a state of virtually un-inhibited motion. Any particle has free access to all parts of the fluidized bed at any given time and is not defined in space except as a function of time. The top level of the bed is a region, rather than line. The general condition of the fluidized regime is one of rapid heat and mass transport. It has been demonstrated many times that the fluidized bed of solids is a remarkably efficient solids mixer. It is readily apparent that there is an immediate distribution of wet feed throughout the bed. The characteristics of the fluidized beds are generally independent of feed condition. It would be appropriate at this stage to discuss the factors that make fluidized bed drying particularly attractive.

A bed of solids in the fluidized condition demonstrates that the highest possible degree of contact exists between the solids and gases, with consequent high heat and mass transfer rates. The drying medium to solids ratio for a specified performance is minimized in the case of fluidized beds. Due to conditions of the high air solids contact and vigorous internal bed mixing, very large gradients of heat and mass transfer can be applied across the bed. Because of very rapid heat and mass transfer, a fluidized bed of material can be subjected to operating conditions that would be deleterious in a packed bed of materials. The solids in a fluidized bed unit can be usually handled as a fluid. By this means flow control and bed level control are greatly simplified. It is possible to carry some material through an extremely difficult range of handling characteristics with relative ease. A fluidized bed unit is selected where floor space is a premium because of lower space requirements. The ease with which multiple units in series or staged arrangement can be adapted results in significant savings in terms of floor area and also in external conveying equipment requirements. Where the drying medium has to be isolated from the surrounding atmosphere, the absence of rotating seals and moving parts become a great advantage.

1.2.1. Advantages of fluidized bed drying

- In fluidized beds, the contact of the solid particles with the fluidizing medium (gas or liquid) is greatly enhanced compared to packed beds. This behavior in fluidized bed drying enables good thermal transport inside the system.

- Good heat transfer between the bed and its container which can have a significant heat capacity while maintaining a homogeneous temperature field.
- High heat and mass transfer rates, because of good contact between the particles and the drying gas.
- Uniform temperature and bulk moisture content of particles, because of intensive particle mixing in the bed.
- Excellent temperature control and operation up to the highest temperature.
- High drying capacity due to a high ratio of mass of air to mass of product.
- Fluidized bed dryer does not require any moving part or rotating seal for which maintenance cost is nil.

1.3. Introduction to fluidized bed dryer

Use of expensive or limited supply of special drying gas indicates profitable use of a fluidized bed dryer. The lack of moving parts in the fluidized bed dryer is a great attraction in troublesome maintenance areas. The above is especially true with corrosive and erosive particles.

Because of the compact size and relatively light weight, it is a unit that can be fabricated in corrosion resistant alloy materials without burdensome costs. An essential factor that is required for design and successful operation of the dryer is the selection of the optimum fluidizing conditions. This is best determined experimentally for the given material in a pilot plant.

Drying is an indispensable process in many food industries and also in many agricultural countries. The large quantities of food products are dried to improve shelf life, reduce packaging cost, lower shipping weights, enhance appearance, encapsulate original flavor and maintain nutritional value [2]. The economic consideration, environmental concerns, and product quality aspects are the main three-fold goal of drying process research in the food industries [3]. The big market for dehydrated fruits and vegetables increases importance of drying for most of the countries worldwide [4].

Fluidized bed dryers provide more efficient air-solid contact and hence, faster drying than any other methods because of homogeneous mixing and uniform drying [5]. The process of fluidization with hot air is highly effective for the drying of powders and wet granular materials. Fluidized bed dryers have many advantages over conventional dryers. In a fluidized bed dryer, fluidization produces full agitation of solid particles by hot air where heat transfer is extremely high and uniform. The product is dried fast without appreciable loss of heat. Adequate drying is an especially important consideration for farmers who plan to store their crop rather than sell it immediately as excess moisture makes stored grain more susceptible to spoilage.

Knowledge on the drying kinetics, as well as the properties and parameters that characterize the drying process of agricultural products has become important in supporting the development of technologies which can assure the conservation of the products. This experimental research has shown improvements all over the world, as can be found in specific literature for post-harvest technology.

The knowledge of mass transfer coefficients for feed samples can provide information about the amount of moisture going to be lost without carrying out real experiments on drying. The prior information on moisture loss during drying period under any condition can lead to a proper dryer design as per the actual requirement which in turn will be very much energy efficient. There is always demand for an economic/cost effective drying operation. This needs a more detailed study on temperature dependence of mass transfer coefficients for different feed samples to be used in the dryer. The knowledge of physical properties of seeds being affected by the moisture content is also necessary for the design of suitable equipment for handling, transporting, processing, and storing the grains. Additionally, information on drying kinetics is necessary for design and prediction of the performance of drying equipment. That is why there is a need for an exhaustive investigation on the effects of the moisture content on physical properties, mass and heat transfer and on the performance of the dryer. It is also felt that there is a need to evaluate the drying kinetics under a suitable operating condition for which information on the effects of different system parameters viz. time, temperature and gas velocity on moisture content is essential. Dependence of moisture loss on system parameters and again dependence of properties of feed, performance of dryer along with heat and mass transfer on moisture loss makes the drying process too much complicated. Interdependence of all the output and input parameters makes the drying process as well as the dryer design more complex for proper analysis for which there is a need for the detailed experimental investigations followed by the validation of the experimental results.

1.4. Introduction to computational analysis

Now a day's several computational/statistical analysis methods are available for validating the experimental data. Both, ANN and Taguchi analysis methods are used to design the experiments and come under statistical types of analysis. ANN analysis is used where more random data are available and Taguchi analysis is used for less data systems.

1.4.1. Regression Analysis:

In statistics, regression analysis includes any techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. More specifically, regression analysis helps one to understand how the typical value of the dependent variable changes when any one of the independent variables is varied, while the other independent variables are held fixed. Most commonly, regression analysis estimates the conditional expectation of the dependent variable given the independent variables that is the average value of the dependent variable when the independent variables are held fixed. In all cases, the estimation target is a function of the independent variables called the regression function. In regression analysis, it is also of interest to characterize the variation of the dependent variable around the regression function, which can be described by a probability distribution.

1.4.2. Artificial Neural Network Analysis:

Artificial neural networks (ANN) are optimization algorithms in which it is attempted to mathematically model the learning process. The model is a simple approximation of a complicated process, but it utilizes the basic foundations and concepts inherent in the learning processes of humans and animals. ANN is universal function approximation that typically works much better than the more traditional function approximation methods. Artificial neural networks can be employed to simulate the non-linear input/output dynamics of a process based on time to process data. Artificial neural network (ANN) is a powerful modelling technique that offers several advantages over conventional modelling techniques because it can model based on no assumptions concerning the nature of the phenomenological mechanisms and understanding the mathematical background of problem underlying the process and the ability to learn linear and nonlinear relationships between variables directly from a set of examples.

An advantage of ANN is the ability to be used as an arbitrary function approximation mechanism that optimizes a criterion commonly known as the learning rule. Also, the neural network makes nonlinear nature processing elements a very flexible system.

1.4.3. Taguchi Analysis:

Taguchi method is used to design the experiments where output serves as the objective functions for optimization, helps in data analysis and the prediction of the optimum results. Taguchi method is a systematic application of analysis of experiments for the purpose of designing and improving product quality. It is used especially for evaluating several process factors at a time with the smallest number of experimental runs based on a table, known as the orthogonal array. The conclusions drawn from small-scale experiments are validated over the entire experimental region spanned by the control factors and their settings. Taguchi design can determine the effect of factors on characteristic properties and the optimal conditions of factors. Orthogonal arrays and ANOVA are used as the tools of analysis. Conventional statistical experimental design can determine the optimal condition on the basis of the measured values of the characteristic properties while Taguchi method can determine the experimental conditions having the least variability as the optimal condition.

1.5. Thesis Outline

The present work on fluidized bed drying of some crops has been reported in the form of a thesis. The thesis comprises of six chapters viz. Introduction, Literature Survey, Experimentation, Results and Discussions, Design of a fluidized bed dryer and Conclusions.

- *Chapter 1* describes the introduction to the present study with the advantages of fluidized bed dryer (FBD), Artificial Neural Network and Taguchi methods.
- *Chapter 2* discusses different research works already carried out in the areas of fluidized bed drying and FBD-simulation using ANN and Taguchi methods. The objectives of the present work are also discussed in this chapter.
- *Chapter 3* discusses about the experimental set up with its various components used for the experimental investigations. Experimental procedure and scope of the experiments are also discussed here in this section.
- *Chapter 4* lists the results obtained from studies of various aspects during experimental investigations. Results for drying kinetics and physical properties analyzed for different crops before and after the experiments are studied. ANN analysis, ANOVA analysis is also carried out on the observed data in this chapter.
- *Chapter 5* describes the design of a tapered fluidized bed dryer with the material and energy balance calculations. Performance of tests for the designed dryer are also carried out in this chapter.

- *Chapter 6* describes the overall conclusions obtained from experimental and simulation studies. The major findings of the work are summarized in this chapter. Future recommendations based on the present research outcomes are also suggested in this chapter.

CHAPTER II

LITERATURE

2.1. Introduction

Drying means removal of water from material. In drying the water is usually removed as a vapour by air. In some cases water maybe removed by mechanically from solid materials by presses, centrifuging and other methods. It is one of the oldest, most commonly used and most energy consuming unit operation in the process industries. Drying is often necessary in various industrial operations particularly in chemical process industries to remove moisture from a wet solid, a solution or a gas to make it dry and choice of drying medium depends on the chemical nature of the materials. The moisture content of the final dried product varies depending upon the type of feed sample. Drying is usually the final processing step before packing and initial step for many chemical processes. Drying processes can be classified as batch, where the material is inserted to the drying equipment and drying proceeds for a given period of time, or as continuous, where the material is continuously added to the dryer and dried material continuously removed. Three basic methods of drying are used today 1) sun drying, a traditional method in which materials dry naturally in the sun, 2) hot air drying in which materials are exposed to a blast of hot air and 3) freeze drying, in which frozen materials are placed in a vacuum chamber to draw out the water. Drying is an important operation in food processing.

Solar grain drying systems at the farm level are under active testing in USA and the results to date suggest that they will soon be widely used. These dryers are replacing expensive fossil-fuel burning dryers and the costs of converting to solar drying can be balanced against reduced fuel bills. Most of these U.S. solar drying systems use large electric fans to circulate air.

In certain climates, some fruits and vegetables can be stored in underground structures and pits. Canning, drying and pickling are other options for fruit and vegetable preservation. The capital costs of containers and the energy requirements for canning make this option out of reach for family level food preservation in most cases, but canning can still be the basis for successful small industries. Drying may be the lowest cost, most widely relevant strategy, especially for fruit preservation [1].Drying is one of several techniques used for preservation and storage of crops.

2.2. Drying Methods

Now a day's many drying techniques are used for preserving foods some of these are discussed below.

2.2.1. Natural Drying Methods:

(i) Field Drying: Many farmers leave their crop in the field to dry. This is especially true for beans and sometimes for maize. Rice should never dry in the field. Using this method the farmer relies on the natural weather conditions (hopefully they are dry enough) to dry his or her crop.

- Advantages:
    - Air passes freely through the field, labour involved is very small.
- Disadvantages:
    - Squirrels, rats, birds, and insects can attack the grain with ease.
    - Grain can fall on the ground and spoil.
    - Often the rainy season makes this type of drying too dangerous.

(ii) Sun Drying: The oldest and perhaps best known drying method is sunning the grain. The harvested grain is spread thinly and evenly directly under the sun on mats, bamboo racks, cement slabs, or tarpaulins. The grain should not be placed directly on the ground.

The grain should be spread on the ground in a layer about 5 to 7.5 cm thick. The grain should be stirred often so that wet grains are brought to the top of the layer to dry and that warm, drier grains are cooled down as they mix with the cooler grain from the bottom. The grain should always be closely watched so that when rain storms come it can be gathered in quickly.

- Advantages:
  - This method dries grain quickly and cheaply.
  - When one stirs the grain often the breeze can pass in between the grain kernels to carry the moisture away.
  - The heat from the sun also bothers the insects; they will not stay in grain which is being sunned.
- Disadvantages:
  - The grain must be brought under shelter every night to avoid the morning dew.
  - Birds, rats, and goats can enter the drying area and eat the grain.
  - Drying during the rainy season is still difficult.

(iii) Natural Air Drying: Many farmers dry their maize using many different types of natural air drying methods. Each of these methods must let the air pass around the kernels to dry them. Therefore, to be completely successful the grains must be exposed to the air.

When drying maize this means that the husks, or leaves, covering the cob of maize should be removed. These leaves are bad for drying for two reasons:

- Many insects can still enter through the leaves and attack the grains.
- It slows down the rate of drying or exposure of crop to air is prevented.

(iv) Direct Fire Drying:

Kitchen Drying: Another effective way to dry grains is by placing the grain in the attic of the kitchen above the cooking fire.

- Advantage:
  - In this case a few leaves can be left on the maize cob so that the smoke does not give the grain a bad taste.

- The heat and moisture are trapped under the zinc roof.

- Disadvantage:

  - As soon as the fire is put out and the smoke stops insects can fly back to the kitchen.
  - Fire wood is very expensive.

2.2.2. *Mechanical Drying [6]:*

Different types of commercial dryers are seen now days. Depending upon the density, shape, size of the materials to be dried and floor room availability, types of dryer can be selected. A glance to different types of dryers can be given as follows.

(i)Tray Dryer: In tray dryers, the food is spread out, generally quite thinly, on trays in which the drying takes place. Heating may be by an air current sweeping across the trays, by conduction from heated trays or heated shelves on which the trays lie, or by radiation from heated surfaces. Most tray dryers are heated by air, which also removes the moist vapours.

(ii)Tunnel Dryer: Tunnel dryer, may be regarded as developments of the tray dryer, in which the trays on trolleys move through a tunnel where the heat is applied and the vapours are removed. In most cases, air is used in tunnel drying and the material can move through the dryer either parallel or counter current to the air flow. Sometimes the dryers are compartmented, and cross-flow may also be used.

(iii) Roller or Drum Dryer: In roller or drum dryer, the food is spread over the surface of a heated drum. The drum rotates, with the food being applied to the drum at one part of the cycle. The food remains on the drum surface for the greater part of the rotation, during which time the drying takes place, and is then scraped off. Drum drying may be regarded as conduction drying.

(iv) Spray Dryer: In a spray dryer, liquid or fine solid material in slurry is sprayed in the form of fine droplet dispersion into a current of heated air. Air and solids may move in parallel or counter flow. Drying occurs very rapidly, so that this process is very useful for materials that are damaged by exposure to heat for any appreciable length of time. The dryer body is large so that the particles

can settle, as they dry, without touching the walls on which they might otherwise stick. Commercial dryers can be very large of the order of 10 m diameter and 20 m high.

(v) Pneumatic Dryer: In a pneumatic dryer, the solid food particles are conveyed rapidly in an air stream, the velocity and turbulence of the stream maintaining the particles in suspension. Heated air accomplishes the drying and often some form of classifying device is included in the equipment. In the classifier, the dried material is separated, the dry material passes out as product and the moist remainder is re circulated for further drying.

(*vi) Rotary Dryer:* The foodstuff is contained in a horizontal inclined cylinder through which it travels, being heated either by air flow through the cylinder, or by conduction of heat from the cylinder walls. In some cases, the cylinder rotates and in others the cylinder is stationary and a paddle or screw rotates within the cylinder conveying the material through.

(vii) Fluidized bed dryers: In fluidized bed drying the process is carried out in a bed fluidized by the drying medium. Usually the drying medium is hot air. Fluidized bed drying produces full agitation of solid particles by hot air where heat transfer is extremely high and uniform. The product is dried fast without appreciable loss of heat. Fluidized bed dryers also provide high drying capacity and lower initial cost.

In a survey conducted in 1972, of dryers used in the chemical industry 5% of all dryer installations are fluid bed, while 16% are rotary. The current trend is towards use of fluid bed in difference to rotary. The survey as projected that in the next two years, fluid bed installations will increase by 30%, while rotary dryers will increase by more 3%. This is indicative of the interest in fluid bed drying.

Dryers can be classified as batch or continuous types depending on the mode of operation. In general batch dryers are preferred for small scale operation and continuous dryer are preferred for large scale operation. Most of the discussion to follow would be in respect of continuous dryers.

The first part of the discussion will discuss the subject from the practical view point of the production engineer. The second part will deal with the theoretical aspects.

It would be of interest to know the range or scope of applicability of these dryers.

1. Throughput – few kg/hr to 500 tons/hr in a wide range of industries, (pharmaceutical, food, fuel and mineral drying).
2. Residence time – a few seconds to many hours.
3. Temperature range – from 800^{o}C to below 0^{o}C.
4. Feed moisture – few percent to a few hundred percent on dry solid basis.
5. Product moisture – few percent to 0.002 percent.
6. Size range – free following material within the size range 0.1 mm to 36 mm

An essential factor that is required for design and successful operation of the dryer is the selection of the optimum fluidization conditions. This is best determined experimentally for the given material in a pilot plant.

2.3. Analysis of Fluidized Drying

It can be classified into two cases.

I. Drying in the dense phase.

II. Drying in the dilute phase, i.e. when material is entrained by the gas stream (pneumatic drying or flash drying). Fluidized drying refers only to dense phase drying.

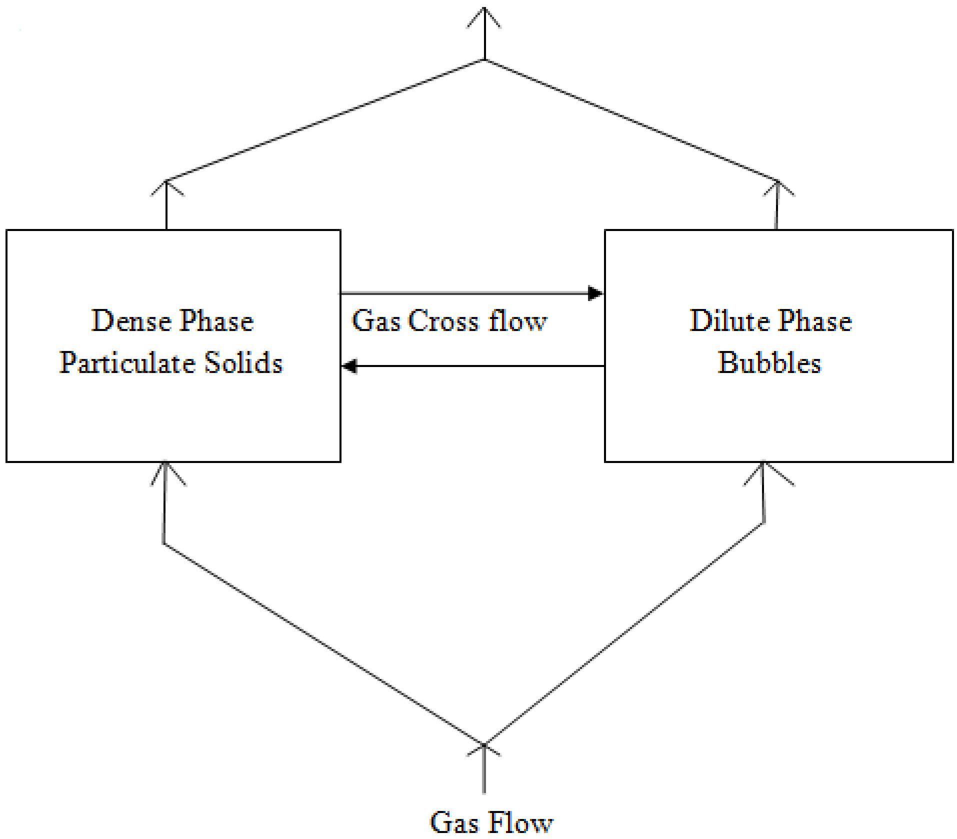


Fig. - 2.1: Schematic diagram of a two-phase model for fluidized bed drying

A simple two-phase model of fluidized bed drying is shown above. The fluidized bed is considered to be composed of a bubble phase (dilute phase) and an emulsion phase (dense phase). The bubble phase contains no particles or the particles are widely dispersed. This model assumes that all gas in excess of minimum fluidization velocity (Umf) flows through the bed as bubbles whereas the emulsion phase stays stagnant at the minimum fluidization conditions.

Drying is essentially a process of simultaneous heat and mass transfer. Heat necessary for evaporation is supplied to the particles of the material and moisture vapours are removed from the material into the drying medium. Heat is transported by convection from the surroundings to the particle surface and from there by conduction in to the particle. Moisture is transported in the opposite direction as a liquid or vapour from the surface; it evaporates and passes on by convection to the surroundings. In most cases, drying involves the application of thermal energy, which causes the liquid, frequently water, to evaporate.

Heat and mass transfer within the solid is intimately related to the mechanism bywhich liquid is removed from the surface and heat is supplied to the surface of the solid. At high external heat and mass transfer rates, the resistance within the solid becomes important. In these conditions, the drying process will be controlled by internal transport. However, the conditions may change during the process. There is a well-established theory for inter phase mass and heat transfer between solid surfaces wetted with a multi component liquid mixture and a hot gas stream.

Drying refers to the removal of moisture or liquid from a wet solid by transferring this moisture into a gaseous state. In most drying operations, water is the liquid evaporated and air is the drying medium.

Drying characteristics of grains are complex. The moisture associated with seeds is of many forms viz. a) chemically bonded b) physico chemically bonded and c) mechanically bound form, depending on the bond strength of moisture. The nature of drying depends on the formation of its bond with the sample. For instance macro-capillary water enters in by liquid flow; on the other hand swelling moisture is removed or dried by diffusion through the cell wall. Hence the removal of moisture from sample becomes difficult.

In a fluidized bed dryer, the feed sample is maintained suspended against gravity in an upward-flowing air stream. There may also be a horizontal air flow helping to convey the feed sample through the dryer. Heat is transferred from the air to the feed sample, mostly by convection.

Recent developments of the regime of fluidization and subsequent design modifications have made fluidized bed drying a desirable choice among other dryers. However, like other types of conventional convective drying processes, fluidized bed drying is a very energy intensive process in industry. The efficiency of a conventional drying system is usually low, depending on the inlet air temperature and other conditions. It is, therefore, desirable to improve the efficiency of the drying process to reduce the overall consumption of energy.

Many studies have been conducted to determine the parameters that affect drying. The way these parameters affect the drying has also been analysed. The main parameters that have been studied are temperature of air, velocity of air, material to be dried, size and shape of the particles, time of drying etc. These parameters help us in optimizing the drying process to reduce the cost and drying times. Also, the increasing cost of energy over recent years has prompted and received great attention in order to increase the convective heat transfer rates in the process equipment.

2.4. Effect of operating parameters on drying

There are many parameters which affect rate of drying. Some of these are discussed below.

2.4.1. Rate of heating:

Heat transfer always occurs from a region of high temperature to another region of lower temperature. Heat transfer changes the internal energy of both the system. The rate of drying is dependent on the rate of heat transfer to the drying material. Heat balance equation assuming loss to the surroundings to be negligible can be written as

$$Q = G\left[\frac{dw}{dz} * \frac{\lambda}{100 - w} + C_m * \left(\frac{d\theta}{dz}\right)\right] \tag{2.1}$$

The above equation can be re-written as

$$C_m * \frac{d\theta}{dz} = \frac{\rho VC(t_1 - \theta)}{G} - \frac{dw}{dz} * \frac{\lambda}{100 - W} \tag{2.2}$$

i.e. heating period ΔZ

$$= \frac{C_m \Delta\theta}{\rho VC(t_1 - \theta) - \frac{dw}{dz} * \frac{\lambda}{100 - W}} \tag{2.3}$$

When the rate of heating the particles is equal to zero,

$$\frac{dw}{dz} * \frac{\lambda}{100 - W} = \frac{\rho VC(t_1 - \theta)}{G} \tag{2.4}$$

Where, Q is the total heat requirement, kcal/hr

θ is the temperature to which sample is heated, ^{o}K

$\frac{dw}{dz}$ is the rate of drying of material,% moisture/hr

$\frac{d\theta}{dz}$ is the rate of heating of material, ^oC/hr

C_m is specific heat of material, kcal/kg^{o}C

G is the weight of material dried, kg

λ is the latent heat of vaporization, kcal /kg

ρ is the density of fluid, kg/m^3

c is the specific heat of fluid, kcal/kg-^{o}C

V is the flow rate of fluid, m/s.

Thus the higher the value of $\rho VC(t_1 - \theta)/G$ and the lesser rate of drying, the higher is the rate of heating. With a given temperature and a given rate of drying, the rate of heating is determined only by the quantity $\rho VC(t_1 - \theta)/G$. It is possible to fix any rate of heating by changing any of the factors in the above quantity. Similarly with a given rate of heating conditions can be so created as to increase the duration of drying and consequently, by choosing suitable parameters, the material can be dried to a greater degree.

2.4.2. Bed density:

In the constant rate period, as it is well known, temperature of the material can be equal to the wet bulb temperature. Hence if the bed density of material is sufficiently high, capacity of the dryer per unit area increases and the gases will leave the bed fully saturated at a temperature equal to the wet bulb temperature. Further increase in the bed density will not be advantageous, because of the quantity of heat given by the gas to the material and the amount of moisture evaporated remain unchanged and pressure drop will be more. On the other hand, if the bed density is sufficiently low, there will be much of heat loss with the exit gases. Besides, the material at this high temperature might be superheated, which is detrimental to heat sensitive materials.

It appears, therefore, that the most suitable bed density should be equal to or greater than the minimum density required for cooling the gas to the temperature of the material.

2.4.3. Velocity:

Increase in velocity gives rise to higher pressure drop; voidage increases and so the height of the dryer has to be increased. Also higher velocity results in production of more fines and consequently difficulty in separation. As a result it has been recommended to operate the dryer at the medium velocity ensuring good mixing in the bed.

2.4.4. Temperature:

It is to be noted from Eq. - 2.2 that at the beginning of drying, when the material is at a lower temperature and the rate of drying is low; heating of the material takes place very fast and afterwards it falls off. In fact, for rapid rate of heating of the material, very high temperature is employed initially. After the material attains the maximum allowable temperature, the temperature is decreased sharply (especially for heat-sensitive materials) and there after it decreases gradually such that the quantity $\rho VC(t_1 - \theta)/G$ changes proportionally with the change in the rate of drying (which evidently falls off with the lowering of moisture content).

While drying gelatine-material in a fluidized bed [2] found that for the removal of the same quantity of moisture, lesser drying time is required at a higher temperature.

2.4.5. Humidity:

Rosenthal et al. [2] have also shown that drying time increases with increase in humidity of the air. Thus, for the removal of the same quantity of moisture, the greater the humidity of air, the greater is the drying time.

2.4.6. *Particle size:*

With increase in particle size the heat transfer coefficient decreases and consequently, the drying rate decreases. For the same period of drying, finer particles are found to have lesser moisture content.

2.4.7. *Residence time in dryer:*

Residence time (also known as drying time) is the average amount of time that a particle remains in contact with the drying medium. Thus this measurement varies directly with the amount of feed sample fluidizing velocity, particle size distribution of the particles and type of operation.

2.5. Drying *Kinetics*

The different terms used during drying experiments are as follows:

2.5.1. *Moisture Content (M_C):*

Percent of Moisture on wet basis is the moisture associated with feed material and expressed as the percentage of weight of feed material.

Weight % of moisture content on wet basis $= \frac{\text{kg of moisture}}{\text{kg of feed}} * 100$ (2.5)

The moisture content lost during drying period under any condition is expressed as a fraction of final weight of the sample and it is given by the following expression [7].

$$M_L = \frac{W_b - W_d}{W_d} \quad (2.6)$$

2.5.2. *Equilibrium Moisture Content (X*):*

Equilibrium moisture content is the moisture content at which the sample is neither gaining using moisture; their however, is a dynamic equilibrium and changes with relative humidity and temperature.

Suppose that a wet solid is brought into contact with a stream of air of constant temperature and humidity in such amount that the properties of the air stream remains constant and that the exposure is sufficiently long for equilibrium to be reached. In such a case the solid will reach a definite moisture content that will be unchanged by further exposure to the same air. This is known as the equilibrium moisture content of the material under the specified condition.

2.5.3. Moisture Ratio (M_R):

Ratio of the mass of moisture lost during drying to the total mass of removable moisture present in the sample at any particular condition (i.e. temperature and pressure).

The average moisture content expressed as non-dimensional moisture ratio [7] is mentioned below.

$$M_R = \frac{(M - M_e)}{M_o - M_e} \tag{2.7}$$

A simple expression of the following form is also developed [7] to model the drying curves.

$$M_R = \exp(-kt) \tag{2.8}$$

2.5.4. Drying Rate:

In air drying, the rate of removal of water depends on the conditions of the air, the properties of the feed sample and design of the dryer.

Qualities of the drying kinetics during drying at different temperatures are compared for natural and artificial drying [8]. Only falling rate drying periods are observed in the artificial oven drying treatments at all the drying temperatures considered. The drying rates are calculated based on the following equation.

$$K_{DR} = \frac{W_b - W_d}{t} \tag{2.9}$$

2.5.5. *Drying Efficiency:*

The thermal efficiency potential for using fluidized bed dryers is strongly affected by the efficient use of energy [9]. Energy efficiency of the fluidized bed dryer based on the first law of thermodynamics can be derived by using the energy balance equation. The thermal efficiency of the drying process can be calculated using the following equation.

$$\eta_c = \frac{\left[h_{fg} * \Delta M_p + W_d * C_m * \left(T_{m2} - T_{m1}\right)\right]}{m_{da} * \left(h_1 - h_2\right) * \Delta t} \tag{2.10}$$

Kazarian [10] compared the results of numerical simulation with the experimental data for drying of wheat grains. It is found that the drying of grains is usually controlled by internal mass transfer parameters in turn by initial moisture content. Thus the initial moisture content of the bed materials has significant effect on the drying rate depending on the physical properties of samples. Assuming wheat grains to be spherical, specific heat of wheat grain is expressed as [10].

$$C_m = 1398.3 + 4090.2\left[\frac{M_c}{1 + M_c}\right] \tag{2.11}$$

Ibrahim et al. [11] studied on Lemon grass in a constant temperature and humidity chamber to examine the effect of temperature and humidity on the drying kinetics. The increase in temperature is observed to increase the drying rates and decrease the equilibrium moisture content (EMC) of Lemon grass. The air humidity is also found to have an adverse effect on the drying process. The drying rates decreased as the humidity increased. But the effect of humidity is observed to be less than that of the temperature as the EMC is found to be high with high relative humidities.

Simplified mathematical models for heat and mass transfer in a fluidized bed dryer have been expressed by Ginzburg [12] where deactivation kinetics of bio-synthesis products during drying is utilized. The effect of longitudinal dispersion on the process and results of fluidized bed drying in a continuous system have also been analyzed by them. Hallstron et al. [13] studied the drying characteristics using granular compounds of mono calcium phosphate fertilizer. Tulasidas et al.

[14] studied the drying kinetics of shelled corn in spouted bed dryer equipped with draft plates. Bilgin et al. [15] predicted drying times in the falling rate period using porous solids in a rotary dryer. Anantharaman and Sundharam [16] analysed drying of Ragi seeds by a fluidized bed infrared drying technique. Simmonds et al. [17] observed that the rate of drying is independent of the air velocity in the range of 1.64m/s to 8.74 m/s. The drying rate is found to be proportional to the free moisture content of the grain while the grain temperature is related to the moisture content at any stage of the drying process. The performance of batch and continuous drying is also compared [18] with an ion exchange resin and sand at 105°C. It is found that batch operations give lower average moisture content for certain drying time. Effects of the gas velocity and the external conditions, such as the humidity are observed to be small on the rate of drying in a fluidized bed dryer [19]. Thomas and Varma [20] investigated batch and continuous fluidized bed drying using granular cellular materials and compared the obtained results for different parameters (viz. temperature, flow rate of the heating medium, particle size and mass of solids in the bed).

Watano et al. [21] studied the effects of the operating conditions on the properties of granules by drying in an agitating tapered fluidized bed dryer. The slow rotational speed, large air velocity and high air temperature are found to increase the drying rate. Chalida and Sakamon [22] studied the effects of various operating parameters, i.e., the values and patterns of inlet air velocity and temperature on the drying kinetics. Krokida et al. [23] studied the drying kinetics and drying constants using various food materials.

Khraisheh et al. [24] observed the Shrinkage of material during the drying process. Shrinkage or change in volume of the food particle is observed mainly due to the removal of moisture. Shrinkage is considered to be important as it influences several other physical properties, such as bulk density, particle shape and size and can also cause internal stresses. Shrinkage also influences moisture removal rate during the drying process. Sahoo et al. [25] observed shrinkage (reduction in volume) of different vegetables and computed the shrinkage constant. The results of drying and shrinkage are compared with the developed correlation and models.

2.6. Moisture Diffusivity

During drying mass transfer takes place because of removal of moisture. Therefore diffusion during drying is known as moisture diffusivity.

2.6.1. Diffusion:

Diffusion is a characteristic behaviour of drying materials where drying or water vapour transfer rates inside the material are controlled by diffusion towards the outer surface. Then, the water vapour concentration on the outer surface of the material becomes very close to equilibrium values. Moisture content increases as a result of increasing equilibrium concentration of the water vapour on the surface of the material at higher temperatures.

Fick's diffusion equation for particles is used for calculation of effective moisture diffusivity. Since the mushrooms are dried after slicing, the diffusivity [26, 27] of the samples is calculated as per the following expression.

$$M_R = \frac{8}{\pi^2} \exp\left(\frac{-\Pi^2 D_{eff} t}{r^2} \right) \tag{2.12}$$

2.6.2. Activation energy (E_a):

The activation energy (E_a) is interpreted as the minimum energy that must be supplied to break water-solid or water-water interactions, and to move the water molecules from one point to another in the solid. The smaller the activation energy (E_a) value for the sample indicates that water molecules can more readily move in the sample. The activation energy required for drying is calculated by using Arrhenius equation [27].

$$\ln(D_{eff}) = \ln(D_o) - \frac{E_a}{R}\frac{1}{T} \tag{2.13}$$

Kossovich and Lebedev [28] formulated the mechanism of moisture transport in the drying of heat sensitive materials in the fluidized bed dryer. Fulford [29] constructed drying-rate curves for the calculation of critical moisture content, drying constant, effective diffusivity of moisture through the slices and energy of activation for diffusion. They also attempted to correlate the process of moisture removal to the process of rehydration. A possible diffusion mechanism based on the concept of internal and external resistances has also been discussed by them.

Gaston et al. [30] observed that the moisture diffusion coefficient of wheat is dependent only on temperature. Efficiency is found to be high at the initial stage of the drying process due to rapid evaporation of the surface moisture of the kernels. But it decreases exponentially during the drying from inside the kernels until the end of the drying process.

Amin et al. [31] experimentally investigated convective drying in a laboratory scale. Experiments are performed at different air temperatures and a constant air velocity of 2 m/s. It is observed by the authors that Logarithmic model out of 12 different thin layer drying models could satisfactorily illustrate the drying curve of bell pepper The high values of coefficient of determination and the low values of reduced chi-square and root mean square error indicated that the Logarithmic models are satisfactory to describe the drying behaviour of bell pepper. The moisture diffusion coefficient is found to be varied between 1.7×10^{-9} and 11.9×10^{-9} m^2/s using Fick's second law for the given temperature range and corresponding activation energy is found to be 44.49 kJ/mol.

Chandrasekar [32] observed that the drying rate increases significantly with increase in temperature and flow rate of the heating medium, however it decreases with increase in solid holdup. The duration of constant rate periods is found to be insignificant considering the total duration of drying. The experimental data are also modelled using fundamental Fick's diffusion equation where the effective diffusivity coefficients are estimated. The estimated effective diffusion coefficients are compared with those of other grains that are reported in literature and the results are found to be within the same order of magnitude.

Meisami-asl et al. [33] experimentally determined the coefficients used in drying models which are essential to predict the drying behaviour. Their studies are conducted to compute effective moisture diffusivity and activation energy of samples of apple slices. The thin-layer drying experiments are carried out under different air temperatures, air velocities and at constant air humidity of 21%. Results indicated that drying takes place in the falling rate period. An Arrhenius relation with an activation energy value of 22664.1 to 30919.0 J/mol and the diffusivity constant value of 1.16×10^{-4} to 6.34×10^{-3} m^2/s are obtained which shows the effects of drying air temperature, air velocity and slice thickness on the diffusivity.

2.7. Mass Transfer

The rate of mass transfer is proportional to the potential (pressure or concentration) difference and to the properties of the transfer system characterized by a mass-transfer coefficient. Initially, the mass (moisture) is transferred from the surface of the material and later, to an increasing extent, from deeper within the particle to the surface and thence to the air. So the first stage is to determine the relationships between the moist surface and the ambient air and then to consider the diffusion through the particle. In studying the surface/air relationships, it is necessary to consider mass and heat transfer simultaneously. Air for drying is usually heated and it is also a major heat-transfer medium. Therefore it is necessary to look carefully into the relationships between air and the moisture it contains.

It is always convenient to define overall mass transfer coefficients based on an overall driving force between the bulk compositions. An overall mass transfer coefficient may be defined in terms of a partial pressure driving force or it may be defined in terms of a liquid phase concentration driving force. In either case, the coefficient must account for the entire diffusion resistance in both phases.

The most widely used mass transfer model of Kunii and Levenspiel [34] expresses the overall mass transfer in a bubbling bed in terms of the cloud-bubble interchange and dense-cloud interchange.

Many researchers [35, 36] have pointed out that; pure diffusion model may significantly under estimate, the overall mass transfer coefficient. It is reported in literature [34] that the true overall mass transfer coefficient may fall closer to either of the acting mechanisms depending on the operating conditions (particle size, gas velocity, etc.).

Makkawi and Ocone [37] have developed a correlation to measure the mass transfer coefficient during drying.

$$K = \frac{A_1 B_1}{d_b^{\,0.5}\left(A_1 + B_1\right)} \tag{2.14}$$

Where,

$A_1 = 0.975\, D^{0.5} (d_b\ g)^{0.25} + 0.25\, U_{mf}\, d_b^{0.5}$

$B_1 = 0.92\, (D_{\varepsilon mf} u_b)^{0.5}$

Where, K(m/s) overall mass transfer coefficient (between dense and bubble phases), A_1, B_1 are parameters (m/s), $U_{mf,}$ minimum fluidization (m/s), d_b bubble diameter, u_b bubble velocity (m/s), $D_{\varepsilon mf}$ bed voidage.

Many researchers [38, 39] have used Sherwood number (*Sh*), to determine the mass transfer coefficient by relating with Schmidt and Reynolds numbers (*Sc* and *R*e). A series of correlations are developed using *S*h, *S*c and *R*e numbers. These dimensionless numbers are expressed as

Reynolds Number: $$\mathrm{Re} = \frac{\rho d v}{\mu} \tag{2.15}$$

Schmidt Number: $$Sc = \frac{\mu}{\rho D_{eff}} \tag{2.16}$$

Sherwood Number: $$Sh = \frac{KL}{D_{eff}} \tag{2.17}$$

Sherwood Number has been related to Reynolds Number and Schmidt Number as per the following equation [40]

$$Sh = 0.664 * (\mathrm{Re})^{0.5} * (Sc)^{0.33} \tag{2.18}$$

This is one method to correlate mass transfer coefficient with the drying parameters.

Ginzburg [41] has simplified the mathematical models of heat and mass transfer during drying in a fluidized bed dryer using the deactivation kinetics of bio-synthesis products. The effect of longitudinal dispersion on the process and results of fluidized bed drying in a continuous system are also analyzed by researcher.

Srinivasakannan and Balasubramanian [42] estimated diffusion coefficient which is found to vary by orders of magnitude with the variation in the column diameter (solid holdup), necessitating the caution one needs to observe while comparing the kinetics of fluidized bed based on the diffusion coefficient.

Kossovich and Lebedev [28] have formulated the mechanism of moisture transport in the drying of heat sensitive materials in the fluidized bed dryer. Drying-rate curves are constructed and used for the calculation of critical moisture content, drying constant, effective diffusivity of moisture through the slices and activation energy for diffusion.

Chandran et al. [43] compared the performance of batch and continuous spiral fluidized bed systems with an ion exchange resin and sand at 105°C. Batch operations are found to give lower average moisture content for certain drying time. The mechanism of heat and mass transfer during the drying of corn kernels in a fluidized bed dryer is also analyzed by Abid et al. [19]. The velocity of the gas and the external conditions, such as the humidity are found to have only a small effect on the rate of drying. The drying characteristics of Ragi seeds were studied in a fluidized bed dryer by infrared drying technique [44].

The diffusivity of the samples is calculated as per the equation - 2.11. Mass transfer coefficient [45 & 46] is then calculated using diffusivity data.

$$K = \frac{S_h * D_{eff}}{L} \tag{2.19}$$

2.8. Physical Properties

Knowledge on physical and mechanical properties of feed samples (seeds /grains) is very important in the design of equipments for handling, drying, aerating, storing structures and processing of the materials. Shape and size of feed sample varies with its moisture content. Recently scientists have made great efforts in evaluating basic physical properties of agricultural materials with their practical utility in machine and structural design and in control engineering [47].Recent scientific developments through mechanical, thermal, electrical, optical and other techniques have improved the handling and processing of bio-materials. However, very little information is known about the basic physical characteristics of bio-materials. Such basic information is important not only to engineers but also to food scientists, processors, plant breeders and other scientists who may find new uses [48].

Knowledge on the properties of grains viz. bulk density, true density and porosity is useful in sizing grain hoppers and storage facilities. These properties affect the rate of heat and mass transfer with different moisture content during the aeration and drying processes. The static coefficient of friction is used to determine the angle at which chutes must be positioned to achieve consistent flow of materials through the chute. Such information is also useful in sizing motor requirements for transportation and handling of grains [49].

The knowledge of various physical and mechanical properties as a function of moisture content is essential to design equipments for their uses in plantation, harvesting, transportation, storage and processing operations of grains/pulses/vegetables [50].

Sobukola and Onwuka [51] Determined of physical properties as a function of moisture content which are important for design of equipment required for handling, conveying, separation, drying, aeration, storing and processing. The shape of the material is important for an analytical prediction of its drying behaviour [52].

Recent developments for the regimes of fluidization and subsequent design modifications have made fluidized bed drying a desirable choice among other dryers. However, like other types of conventional convective drying processes in industries, fluidized bed drying is a very energy intensive process. Many researchers have analyzed experimental and simulation studies on fluidized bed drying.

The geometric mean diameter (Gm) of the grain is calculated by using the axial dimensions as per the following expressions [53].

$$D_g = (LW'T')^{\frac{1}{3}} \tag{2.20}$$

The sphericity (ϕ) of grain is expressed as [53**]**.

$$\phi = \frac{(LW'T')^{\frac{1}{3}}}{L} \tag{2.21}$$

The grain volume (V) and surface area (S_a) of the grain, depending on the shape of grain are calculated as per the following equations [54].

$$V = \frac{\pi B^2 L^2}{6(2L - B)} \tag{2.22}$$

$$S_a = \frac{\pi B L^2}{2L - B} \tag{2.23}$$

Where B = $(WT)^{0.5}$

The bulk density of grain is determined as per the following equation [54].

$$\rho_b = \frac{G_2 - G_1}{V_b} \tag{2.24}$$

The true density of grain is calculated using following equation [54].

$$\rho_t = \frac{W_l + W_s}{V_l + V_s} \tag{2.25}$$

The porosity (ε) of grain sample is computed from the values of bulk density ρ_b and true density ρ_t using the following equation [55].

$$\varepsilon = \frac{\rho_t - \rho_b}{\rho_t} \tag{2.26}$$

2.8.1. Volume Ratio:

The relationship between drying constant and shrinkage constant of different shaped feed samples with different geometrical shapes and different aspect ratios are studied in fluidised bed drying. Simple mathematical models are also obtained for volumetric shrinkage constant and drying constant [56].Volume ratio is defined as the ratio of volumes of samples before and after drying. Volume ratio is related to moisture ratio and is expressed below.

Senadeera [57] suggested the effect of temperature on material during drying and plasticizing effect of water on amorphous materials. The following correlation was developed by author to study the shrinkage of particles.

$$V_R = 1 - Be^{kM_R} \qquad (M_R \leq 1) \tag{2.27}$$

The effect of shrinkage during drying of Potato spheres and the effect of drying temperature on vitamin-C retention was studied by Mclaughlin and Magee [58] Drying of potato spheres was found to be almost ideally three dimensional and drying rate curves were found to contain two distinct falling rate periods. Vitamin C was found to degrade exponentially which is described well over the temperature range 30-60°C.

Togrul and Pehlivan [59] investigated the transfer of moisture from the apricots during the falling-rate period of drying and analysed the apparent diffusion coefficient. It was found out that the diffusion coefficients can be expressed within 97.3% accuracy depending on the air flow rates and inside temperatures of the bed material.

Senadeera and Desbiolles [60] established the relationship among time and shrinkage constants during drying of different shaped samples. Time based volumetric shrinkage coefficients were modelled and observed to be varied with drying temperature and proportion of the samples.

Senadeera et al. [61] studied the fluidization characteristics of moist food particles where the changes in fluidization behaviours with moisture content were observed and fitted to a linear model. A generalised mathematical model was also formulated for the varied bed height.

The effect of particle size distribution (PSD) on local voidage was investigated in a conical fluidized bed with dried placebo pharmaceutical granule by Tanfara and Pugsley [62]. For each of the five PSDs examined, the static bed height and the superficial gas velocity were varied. The mixtures containing less coarse material exhibited a centrally concentrated gas flow surrounded by a dense phase at the walls of the bed over the entire range of gas velocities and bed heights examined.

LUZ et al. [63] investigated the effect of different temperatures and air speeds onthe drying kinetics for the soybean meal drying and found to have significant influence on the (K) the mass transfer coefficient. The limiting step for mass transfer is found to be occurred in the interior of the particle. A model was also developed to evaluate K.

Hassanain [64] carried out simple solar drying for banana fruit and observedthe horizontal dryer chamber to be better over the vertical one. The drying efficiency for the forced convection was found to be higher for the first day comparing with the following days due to the fast drying in the moisture falling stage.

Benali and Amazouz [65] discussed the drying of vegetable starch solution on the inert particles where quality and energy aspects are analysed. The initial moisture content and the position of an atomizing device were found to be key factors to determine the quality of product and efficiency of the system.

Ndukwu [66] observed the drying constant and drying rate for Cocoa Bean to be affected by drying temperature and air velocity which shows cocoa bean drying to occur on the falling rate.

Methods of improvement of energy utilization were evaluated and reduction of energy cost in conventional unpeeled long a drying was estimated by Tippayawong et al. [67]. The improvement was attributed to fuel switching from liquefied petroleum gas to wood, heat recovery via hot air recirculation, better temperature and humidity control, and thermal insulation. The new dryer with improved design and better energy efficiency was estimated to have payback period less than 3 years.

Timothy et al. [68] studied the efficiency of 'corona wind' drying and its application to the food industry. Experiments using the corona wind to evaporate water from paper towels and biscuits shows significant drying enhancement at an overall efficiency comparable to convention drying methods.

Kingsly et al. [69] discussed shrinkage of ber fruits during sun drying. Shrinkage during drying was observed to play an important role in determining the quality of the dried product. It was also observed that the shrinkage is directly proportional to the amount of removal of moisture from the fruits.

Talla et al. [70] discussed on the variation in density and shrinkage for banana during its drying by proposing a mathematical model which may further improve the modeling of the drying kinetics of this product and the determination of its various characteristics.

Walde et al. [71] discussed the effects of parameters like blanching, blanching followed by soaking in potassium meta-bisulphite (KMS), fermented whey, curds, etc. and dried in different dryers viz, hot air cabinet dryer, fluidized bed dryer, vacuum dryer and microwave oven on dehydration of mushroom. The effect of drying methods was expressed by a polynomial equation. The fluidized bed drying was observed to be a promising method for drying mushrooms, when comparing the lower drying time and good quality products.

2.9. Analysis using Artificial Neural Network

As an alternative to these parametric models, the use of Artificial Neural Networks stands out. The researchers aroused great interest in recent years because of their ability to efficiently correlate nonlinear multidimensional spaces. Among the simulation techniques, Artificial Neural Networks (ANNs) have high learning ability and capability of identifying and modelling the complex non-linear relationships between the input and the output of a system. Drying is quite complex and uncertain which can be considered as non-linear, time-varying process functions of many unknown factors. This phenomenon has been modelled with different levels of complexity.

Hence, the potential of Artificial Neural Networks as universal approximates can be explored and the usefulness in predicting the values of process output variables from independent input variables for fluidized bed dryer can be studied.

The available data set is divided into two parts one corresponds to training and the other corresponds to validation of the model or testing. The purpose of training is to determine the set of connection weights and nodal thresholds that cause the ANN to estimate outputs that are sufficiently close to target values. The complete data to be employed for training should contain sufficient patterns so that the networks can establish under-laying relationship between input and output variables. During training, those are adjusted based on the error or difference between ANN output and target responses.

Artificial Neural Network (ANN) have shown increased ability for solving non-linear problems in the field of food processing. Neural networks are also found to be useful when no exact mathematical information is available. During last few years, interest in using Artificial Neural Networks (ANN) as a modelling tool in food technology has increased. ANN have been successfully used in several food processing applications like model for prediction of drying rates, physical properties of dried carrot, prediction of dryer performance, extrusion processing of wheat and wheat-black soybean, energy requirements for size reduction of wheat, grain drying process etc.

In the present work ANN has been applied to a fluidized-bed dryer to predict the moisture and temperature of the product. Inlet and outlet air temperature, absolute humidity and air flow have been used as the input variables to the layers of the ANN. The moisture content of the solid obtained from drying operation are predicted, modelled and the fluidized-bed drying process is optimized using an ANN structure with three layers, five inputs, four hidden neurons, and one output.

2.9.1. Back Propagation Neural Network:

Back-propagation is a multilayer neural network and is used for systematic training of data. It is built on high mathematical foundation and has very good application potential. Even though it has own limitations, it is applied to a wide range of practical problems and has successfully demonstrated its power. The back propagation refers to the fact that any mistakes made by the network during training is sent backwards through it in an attempt to correct and so teach the network what's right and wrong. This back propagation network (BPN) uses the gradient descent learning method, which represents the error function as it tries to find the minimum of the error function and by doing so decrease the error. Back propagation learns by iterative processing of a set of training data (samples). For each sample, weights are modified to minimize the error between network's classification and actual classification.

A three layered feed forward Back-propagation network consists of the following layers:

- an input layer
- at least one intermediate hidden layer
- an output layer

Schematic representation of ANN-Structure has been shown below in Fig. - 2.2.

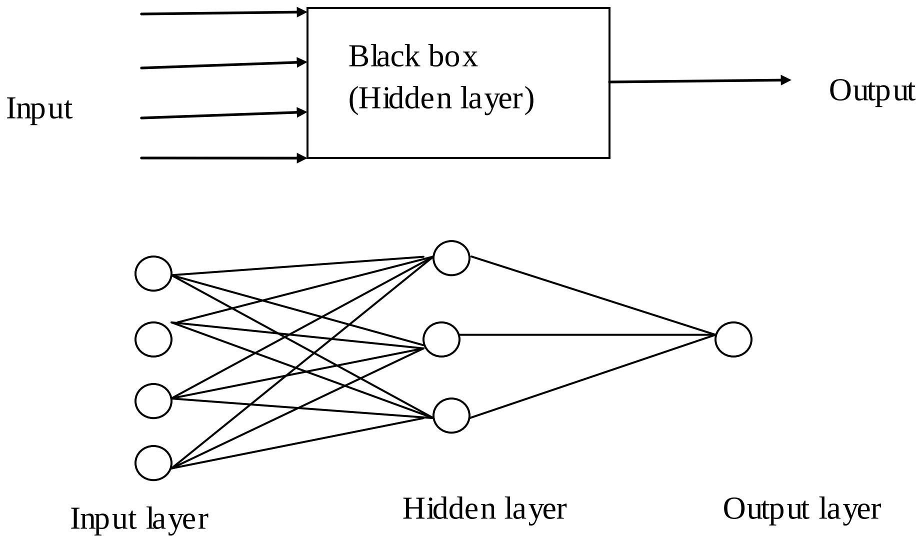


Fig. - 2.2: Schematic representation of ANN-Structure

- The network is trained for a given set of input and target data sets.
- The sigmoidal activation function is expressed as follows [72] :

$$f(x) = 2.0 * \left(\frac{1}{1 + e^{-2x}} - 0.5 \right) \tag{2.28}$$

Satish and Setty [73] experimented on drying of solids in a continuous fluidized bed dryer with different variables like bed temperature, gas flow rate, solids flow rate and initial moisture content of solids. The data are modelled using artificial neural networks. The results obtained from artificial neural networks are compared with those obtained from experiments using Tanks-in-series model. It is found that results obtained from ANN fit the experimental data more accurately compared to the RTD model with less percentage of error. This indicates superiority of artificial neural networks to experimental data compared to various other mathematical models.

Nazghelichi et al. [74] used static and recurrent artificial neural networks (ANNs) to predict the drying kinetics of carrot cubes during fluidized bed drying. Static ANN are used to correlate the outputs (moisture ratio and drying rate) to the four exogenous inputs (drying time, drying air temperature, carrot cubes size, and bed depth). In the recurrent ANNs, in addition to the four exogenous inputs, two state input and output (moisture ratio or drying rate) are applied. A number of hidden neurons and training epoch are investigated in this study.

Amiri et al. [75] determined the thermo-physical characteristics of pistachio and predicted at a range of temperatures (50 to 95°C) and moisture contents (3.8 to 52.15% dry basis) using line heat source method and Artificial Neural Networks (ANNs). Two independent variables i.e. temperature and moisture content are considered as inputs of ANNs and thermal conductivity are considered as an output variable. It is observed that decreasing moisture content reduces thermal conductivity, but decreasing it further causes the proportionate increase in thermal conductivity of the samples. They further found that prediction accuracy of thermal conductivity by designed ANN is better than statistical results.

Tiwari and Pandey [76] modelled the high velocity hot air recirculatory tray drying of treated and untreated sweet pepper slices which are carried out using artificial neural network and response surface methodology. Drying air temperature, drying air velocity and slice sizes are considered as the independent variables where drying rate, moisture ratio during drying, the rehydration ratio and sensory quality of the dried slices are measured as the dependent variables. The models obtained are compared and it is observed that the ANN model is best suitable to predict the dependent responses as compared to the response surface methodology (RSM) model.

Shivmurti & Kumbhar [77] determined the drying characteristics. The analytical model and Artificial Neural Network (ANN) model for low pressure superheated steam drying are studied. Effects of steam temperature and pressure on drying rates are determined. Second degree polynomial, nonlinear regression analysis resulted in a good agreement of defined model by changing the values of temperature and corresponding pressure. Optimized ANN models are developed for all data set. The correlation coefficient for all data set is >0.98 in all cases.

Marius et al. [78] developed Artificial Neural Network (ANN) modelling of gas drying by adsorption in fixed bed of composite materials. The experimental investigations are carried out at two values of relative humidity and three values of air flow rate respectively. The experimental data are employed in the design of the feed forward neural networks for modelling the evolution in terms of some adsorption parameters.

Menlik [79] used the freeze drying process based on different parameters, such as drying time, pressure, sample thickness, chamber temperature, sample temperature and relative humidity. An artificial neural network model has been developed for the prediction of drying behaviours, such as M_C and M_R of strawberries in the freeze drying process.

Koni et al.[80] investigated the drying of baker's yeast in a fluidized-bed dryer. Mathematical modelling of the process is carried out, incorporating the important process and quality parameters of the system. Artificial neural network (ANN) and adaptive neural network-based fuzzy inference system (ANFIS) structures are used to create process and quality models. ANN quality modelling are performed using process output parameters and the quality losses incurred from drying the product are also determined.

Zhang and Yang [81] used Artificial Neural Networks (ANN) and developed modelling for rough rice drying. The ANN outputs are the six performance indices: energy consumption (EC),kernel cracking (KC), final moisture content (FMC), moisture removal rate (MRR), drying intensity (DI) and water mass removal rate (WMRR) and the inputs are the four drying parameters: rice layer thickness (RLT), hot airflow rate (HAR), hot air temperature (THA) and drying time (DT). The optimal model is a four-layered back-propagation neural network with 8 and 5 neurons in the first and the second hidden layers respectively. The effectiveness of the proposed model is demonstrated using experimental data.

Khoshhalet al. [82] used Artificial Neural Network (ANN) modelling. Several mathematical models are also applied to predict the moisture ratio in an apple drying process. Four drying mathematical models are fitted to the data obtained from eight drying runs and the most accurate model is selected. The results show that the ANN predictions are more accurate in comparison with the best fitted mathematical models. In addition, none of the mathematical models is able to predict the effect of the four input parameters simultaneously, while the developed ANN model predicts this effect with a good precision.

2.10. Taguchi Analysis

Taguchi approach has successfully been applied in several industrial organizations changing their outlook to quality management. It is based on three simple yet powerful fundamental concepts [83].Taguchi philosophy is to design the quality into the product rather than to inspect for it after its production. Quality improvement should begin at the very beginning i.e. during the design stage of the product development and should continue through the production process. Dr Taguchi observed that no amount of inspection could put quality back into the product and it only treats the symptom. Therefore he argued that quality concepts should be based upon and developed around the philosophy of prevention [83].

In Taguchi method, the signal to noise ratio (S/N) is used to measure the quality characteristics deviating from the desired value. The signal to noise ratios (S/N) are log functions of desired output, serve as the objective functions for optimization, help in data analysis and the prediction of the optimum results.

Since in the present work there is only one replication, further analysis of orthogonal array (OA) is done through ANOVA. The method used to compare the treatment means which is known as analysis of variance, or ANOVA. An ANOVA Table breaks down the effect of each factor and the experimental error. In addition, it also breaks down all of the possible interactions of the factors.

2.10.1. Optimization by design of Experiments (DOE) [84]:

Design of Experiments (DOE), is a tool to develop an experimentation strategy that maximizes learning using a minimum of resources. To develop new products and processes in a cost-effective and confident manner, experimental design techniques become extremely important to explain the statistical significance of an effect that a particular factor exerts on the dependent variable of interest.

2.10.2. Scope:

It helps in

- Identifying relationships between cause and effect.
- Providing an understanding of interactions among causative factors.
- Determining the levels at which it is required to set the controllable factors (product dimension, alternative material, alternative designs, etc.) in order to optimize reliability.
- Minimizing experimental error (noise).
- Improving the robustness of the design or process to variation

In the optimization process, appropriate selection on DOE is important before the analysis. For four levels and three factors, a standard L16orthogonal array is chosen. This orthogonal array is chosen due to its minimum number of experiment trials. The experiment trial is represented by each row in the matrix.

2.10.3. Application:

Experimental design is a critically important tool in the engineering world for improving the performance of a manufacturing process. It also has extensive application in the development of new processes.

The application of experimental design techniques early in the process development can be resulted in

- Improving process yield
- Reducing variability and closer conformance to nominal or target requirement
- Reducing development time
- Reducing overall costs

Experimental design methods also play a major role in engineering design activities, where new products are developed and existing ones are improved. Some applications of experimental design in engineering design include:

- Evaluation and comparison of basic design configurations
- Evaluation of material alternatives
- Selection of design parameters so that the product will work well under a wide variety of field conditions, these are robust
- Determination of key product design parameters that can impact product performance.

2.10.4. Working Principles:

Taguchi method employees an efficient methodology to optimize only a single performance characteristic and is widely being applied now-a-days for continuous improvement. It produces better quality products at a low cost [85].

Taguchi's concepts can be summarised as follows:

1. Quality should be designed into the product and not inspected into it.
2. Quality is best achieved by minimizing the deviation from the target. It is immune to uncontrollable environmental factors.
3. The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

According to Taguchi, Quality characteristics are of three types as shown below.

1. Nominal-the-Best (NTB) or Target-the-Best (TTB)

2. Lower-the-Better (LTB)

3. Higher-the-Better (HTB)

Only 'the lower the better' and 'the higher the better' are applicable in optimization of moisture contents and drying rate respectively. For criterion of 'the smaller the better', the following formula is used to calculate Signal-Noise (SN) ratio to minimize moisture contents.

$$SN = -10\log 10\left(\frac{y_i^{\;2}}{n}\right) \tag{2.29}$$

Where y_i is the measured data and n is the quantity of measured data.

'In contrast, "the bigger the better" criterion is applied as a criterion for the drying rate as the highest rate of drying is desired. The SN ratio for this criterion is determined using the following equation.

$$SN = -10\log 10\left(\frac{\sum \frac{1}{yi^2}}{n}\right) \tag{2.30}$$

2.11. Analysis of Variance (ANOVA)

Experimental factors influence the response and so this will be due to unknown causes or measurement errors in experiments, there exists some variability. Every experimental data set is most likely to show certain variability, but whether such change is due to input factors or due to random factors is to be answered by ANOVA. The method tries to carry out the following.

- Decomposes the deviation of the experimental data in relation to possible sources; the source may be from the main effect, from the interaction, or maybe from experimental error.
- Measures the magnitude of variation due to all sources.

• Recognize the main and interaction effects which have significant effects on variation of data.

2.11.1. Calculation of the appropriate test statistics:

Total Sum of Squares (SST), Total Mean Squares (MST), F-value, $SS_{Regression}$, and SS_{Error} are calculated using the following formula:

$$SS_{Total} = \sum_{i}^{n}\sum_{j}^{r}\left(y_{ij} - \overline{y..}\right)^2 \tag{2.31}$$

$$SS_{Error} = \sum_{i}^{n}\sum_{j}^{r}\left(y_{ij} - \hat{y}_i\right)^2 \tag{2.32}$$

$$SS_{Regression} = SS_{Total} - SS_{Error} \tag{2.33}$$

Where $y_{ij} = i^{th}$ observed response of j^{th} replicate, $\hat{y}_i = i^{th}$ = i^{th} fitted response, and $\overline{y..}$ =mean of all (n × r) observations.

(i) Mean Square:

$$\text{Total Mean Squares (MST)} = \frac{SST}{N-1} \tag{2.34}$$

Where, N is the total number of observations

$$\text{Mean Square Treatment (MSTR)} = \frac{SSTR}{C-1} \tag{2.35}$$

Where, C is the number of columns in the data table)

$$\text{Mean Square Error (MSE)} = \frac{SSE}{N-C} \text{ “average within variation”} \tag{2.36}$$

(ii) F-value:

$$F = \frac{MSTR}{MSE} \tag{2.37}$$

Larger values of F support rejecting the null hypothesis which indicates that that there is no significant effect.

(iii) P-value:

In statistics, the p-value is a function of the observed sample results that is used for testing a statistically hypothesis. Before the test is performed, a threshold value is chosen, called the significance level of the test and is denoted as α.

Kumar et al [86] have discussed that the Taguchi's design can further be simplified by expanding the application of the traditional experimental designs to the use of orthogonal array. This method is a simple, efficient and systematic approach to optimize designs for performance, quality and cost.

Ho-Hsien et al. [87] applied the Taguchi method to determine optimum extraction conditions of ginger drying to produce a high yield of ginger oil. The control factors included reaction time, drying temperature, extraction pressure and particle size of the ginger powder. In addition to these results, the study founds that high temperature would cause starch gelatinization, which might affect the extraction process and produce a lower yield of ginger oil.

Siti et al, [88] discussed the application of Taguchi method in optimizing the drying parameters of orange peels using a fluidized bed dryer. ANOVA analysis method is used to determine the contribution factor of each parameter during the drying process. It is observed that orange peel to sand mass ratio factor contributes more to drying than air temperature and velocity.

Naik [89] studied the optimum parameter for high percentage of yield by varying parameters through Taguchi method. Taguchi method is observed to be an efficient method of determining the optimum parameters for high percentage of yield. ANOVA helped to estimate the contribution of each noise factor.

Semra [90] concluded that Taguchi Method is one of the most frequently used methods especially in optimization problems. But applications of this method are not common in food industry. In his study, optimal operating parameters are determined for industrial scale fluidized bed dryer by using Taguchi method.

Navanth [91] investigated that Analysis of variance (ANOVA) which is employed to determine the most significant control factors affecting the surface roughness and whole diameter. The main and interaction effects of the input variables on the predicted responses are found. The predicted values and measured values are found to be fairly close to each other.

Rama Rao [92] investigated the effects of process parameters which are determined by using Taguchi's experimental design method. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA) and regression analyses are employed to find the optimal process parameter levels and to analyze the effects of these parameters on values of metal removal rates. Confirmation test is carried out with the optimal levels of machining parameters in order to illustrate the effectiveness of the Taguchi method.

Mustafa [93] confirmed tests with the optimal levels of machining parameters in order to illustrate the effectiveness of the Taguchi method. The validity of Taguchi's approach to process optimization is found to be well established.

Rahman [94] determined the optimum conditions of humidity contents, drying rate and energy in the drying experiment for lemon grass using the fluidized bed dryer in presence of inert particles. The optimization methods by Taguchi, ANOVA methods are found to be the most appropriate statistical method to optimize the data due to its simplicity.

Tasirin [95] investigated humidity contents and drying rate using both conceptual S/N ratio and ANOVA approaches which lead to a similar conclusion. Taguchi method of design of experiment is found to be suitable to be applied for optimization of chemical processes generally and particularly in drying processes. Overall, the most significant factor in controlling the humidity contents and drying rate is the drying time.

Phadke [96] analysed the means and S/N (Signal to Noise) ratio using a conceptual approach that involves graphing of the effects and visual identifying of the factors that appear to be significant, without using ANOVA, thus making the analysis simple.

From the above studies it is observed that drying characteristics of crops and performance of dryer not studied together. Many researchers have focused only on drying kinetics. Some have focused on performance of dryer only. Very few researchers have focused on changes in physical properties of materials during drying that to in oven drying only. Almost no one has related physical properties of feed materials with the efficiency of the dryer. Again fluidized bed is observed to perform better drying in comparison with other commercial dryers. In view of these studies observed through literature survey the objectives of the present work are finalised and listed below.

2.12.Objective of the work

- To study the drying characteristics (mainly the moisture loss, diffusivity, and mass transfer coefficient) for different crops using a fluidized bed dryer.
- To study the changes in physical properties (such as Surface area, Volume, Sphericity, Bulk density, True density and Porosity) with the changes in moisture content for different crops using a fluidized bed dryer.
- To study the performance in terms of efficiency of dryer using different crops.
- To validate the experimental results using ANN and Taguchi Analysis.
- Design of fluidized bed dryer with material balance and energy balance calculations.
- To carry out performance tests for the designed dryer using difference crops.

CHAPTER III

EXPERIMENTAL ASPECTS

Some crops(grains and vegetables)are considered to study the drying kinetics and physical properties in a fluidized bed dryer. A fluidized bed dryer as shown in Fig. - 3.1(A) & 3.1(B) is used for the present study. It is aimed to study the effect of different system parameters on drying kinetics, heat & mass transfer and physical properties of materials using the fluidized bed dryer. Various system parameters studied for different aspects of fluidized bed drying in the present work are listed in Tables - 3.4 – 3.6 as scope of the work.

3.1. Experimental set up

The sectional views and schematic diagram for the experimental unit are shown in Fig. - 3.2(A) &3.2(B) respectively. Different parts of the experimental set up are discussed below.

Fig. - 3.1(A): Fluidized bed dryer (Laboratory set up)

Fig. - 3.1(B): Experimental setup in the running condition

3.1.1. Tapered Fluidized Bed Dryer:

The column is shaped like a truncated cone with bottom diameter12.1 cm and top diameter 21.96 cm. The column height is 20 cm. The cone angle is 14°.

3.1.2. Gas Distributor:

A gas distributor is attached at the bottom end of the column. The distributor is a 2mm thick plate with 2mm perforations. A fine wire mesh of 0.2mm openings is spot welded over the distributor plate to arrest the flow of solids from the fluidized bed into the air chamber.

3.1.3. Electrical Heater:

The electrical heater consisted of multiple heating elements of 2 KW rating. Air from the blower is heated and fed into the air chamber and then in to the fluidization column.

3.1.4. Temperature controller:

A temperature controller is provided to the air chamber which facilitates the control of air temperature to ± 0.5°C for the operating range of 40°C -110°C.

3.1.5. Timer:

The timer is provided in which time for drying can be maintained.

3.2. Experimental Procedure

The experiments are carried out in batch mode. For fluidization experiments, the fluidized bed dryer is connected to a heat pump dehumidifier system. The drying conditions are set by the temperature controller in the heat pump dehumidifier system by setting at different temperatures. The drying set-up is made to run for 10 minutes to achieve steady state conditions of drying before material introduction. Dryer is filled with the known amount of feed samples and allowed to run till the steady state condition is achieved and readings are observed at 10 minutes interval after the steady state is reached. The feed samples are subjected to drying for required time period at the steady state condition. The hot air velocity passing through the bed material is maintained at a constant value for a single set-up experiment. Samples are taken out of the dryer at 10 minutes interval of time for measuring the weight after drying. Loss in moisture content is determined by the difference between weights of the sample before and after drying.

In the present work the drying kinetics of different grains and vegetables are analyzed in terms of moisture content, diffusivity, mass transfer coefficient and physical properties. The picture of different grains, vegetables and mushroom are shown in Fig. - 3.3(A), Fig. - 3.3(B) & Fig. - 3.3 (C) respectively. The effects of different system parameters such as drying air temperature, drying time, density of materials, shape factor (i.e. L/D ratio) and air velocity on the drying kinetics are studied. Initial moisture content of the sample is determined as percentage by weight with the help of a moisture analyzer. A weighed amount of sample is taken in the dryer. Time, temperature and velocity are set for the experimentation. Then the power supplied to the unit and dryer is made to run. As the drying operation gets over the material is taken out and weighed. The difference in weight gives the idea of moisture loss from the sample.

3.3. Determination of physical properties

Initially different dimensions of the samples are measured which are listed in Table - 3.1. Grains are soaked and used for the drying experiments. Dimensions of the soaked grains are measured (Table - 3.2) before experiments. Different physical properties such as geometric mean diameter, sphericity, volume, surface area, bulk density, true density and porosity of grains and vegetables (feed samples) are measured at room temperature before drying experiments (Table - 3.3). Different physical properties of samples are again determined at the second level of moisture content. The procedure is repeated for different feed samples and for different drying conditions. The physical properties of samples are also computed at different levels of moisture contents which are obtained by varying different system parameters during drying. Methods for determination of different physical properties of grains are explained below.

3. 3.1. Axial Dimensions:

To determine the average size of grain, 10gm of feed sample is randomly selected at any particular condition during the experiment. Three axial dimensions namely, length (L), width (W) and thickness (T) of the sample are measured using a digital calliper with 0.01mm least count.

3.3.2. Bulk density:

Certain volume of water is taken in a container. Then known amount of sample is taken in it. Amount of water displaced gives the volume of sample. Dividing the weight of the sample with its volume gives the bulk density.

3.3.3. True density:

- The above method is also used to determine the true density of samples. Where as toluene (C_7H_8) is used in place of water. Toluene is absorbed to a lesser extent by the samples.

3.4. Regression Analysis

Regression analysis is used in the present work correlate different independent system parameters to one dependent system parameter. In the present work, time, temperature of drying, velocity of hot air and density/aspect ratio of the bed materials are considered as the independent system parameters while moisture content/diffusivity of air/mass transfer coefficient/efficiency is considered as dependent system parameter depending upon the drying aspects. Different physical properties of the feed samples are also considered as the dependent system parameters. The general form of the correlation developed on the basis of regression analysis is described below.

$$X = K'\left[t^a \theta^b u^c \rho^d\right]^n$$

Where t, θ, u, ρ are independent parameters.

a, b, c, d are exponents of the individual parameter.

n is the overall exponents and K' is the overall coefficient of expression.

X is the dependent parameters or output of the system.

3.5. Analysis using Artificial Neural Network

The feed forward back propagation three layered ANN has been used in the present study to validate the developed correlation for drying kinetics on the basis of regression analysis. The three layers in ANN are known as input, hidden and output layers. The input layer has five nodes, representing drying time (t), temperature (θ), velocity (U_o), density (ρ) and L/D ratio, moisture content/diffusivity of air. The output layer has six nodes i.e. a, b, c, d, K' and n (exponents and coefficients of correlation). From the experimental data, one dataset is randomly selected as testing set and another four datasets prepared by manipulation are used for training. Network performances are evaluated by comparing the ANN - training output against those of the testing data and analyzing the root mean square (RMS) error between the normalized and experimental data over 5000 to 20000 number of epoches or cycles. The numbers of neurons in this hidden layer are varied to find the architecture that provides the least error and thereby the optimum ANN - structure is determined. The different ANN-parameters for three layered, Back Error Propagation type network is given in Table - 3.7.The optimum ANN – structure is shown in Fig. - 3.4.

3.6. Taguchi Method

Taguchi design method is studied with different parameters. Three parameters namely, time, temperature and velocity are considered as three factors which are adopted at each level. The fractional factorial designs are used in a standard L16 orthogonal array. This orthogonal array is chosen because of its minimum number of experiment trials. Each row of the matrix represents the trial. However, the sequence in which these trials are carried out is taken as randomly represented four levels of each factor in the matrix. Taguchi method is mainly used to achieve high quality and to reduce effectively the number of experimental trials. The control factors shown in Table - 3.8 include different levels of three factors time, temperature and velocity. L16 orthogonal arrays are selected for the experiments, and there are 16 experimental runs with 3 factors (columns) and 4 levels (rows). By using the L16 orthogonal array for Taguchi method, a total of 16 sets of experiments are listed and shown in Table - 3.9.

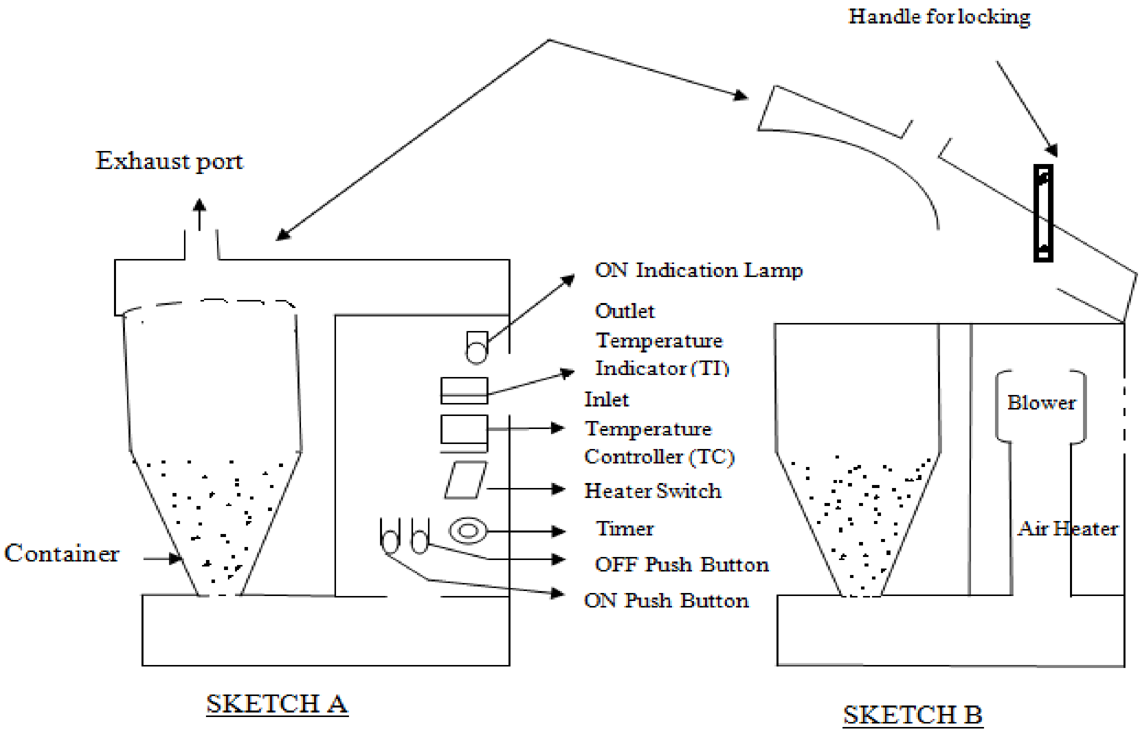
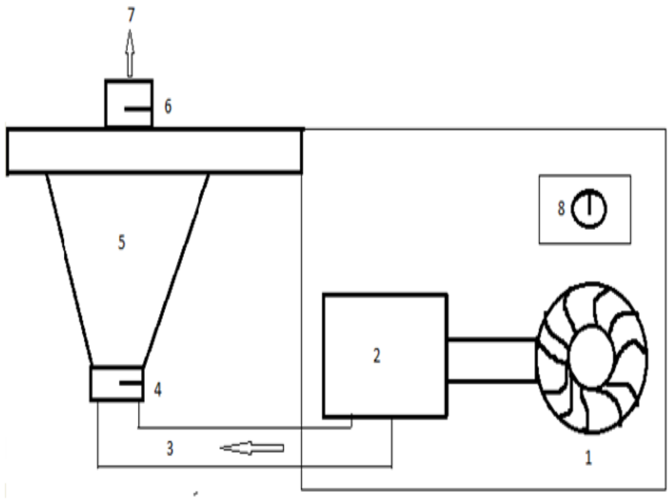


Fig. - 3.2(A): Sectional views of Fluidized bed dryer



1.	Air Compressor	5.	Tapered Fluidized Bed
2.	Heater	6.	Outlet Hot Air Temperature Sensor
3.	Air inlet to the bed	7.	Hot Air outlet
4.	Inlet air temperature sensor	8.	Timer

Fig. - 3.2(B): Schematic diagram of the experimental unit.

Red kidney bean

Bean seed

Wheat

Rice

Fig. - 3.3(A): Pictures of different grains used in drying experiments.

Ladies Finger

String Beans

Radish

Ivy Gourd

Fig. - 3.3(B): Pictures of different vegetables used in drying experiments.

Fig. - 3.3(C): Picture of mushroom used in drying experiments.

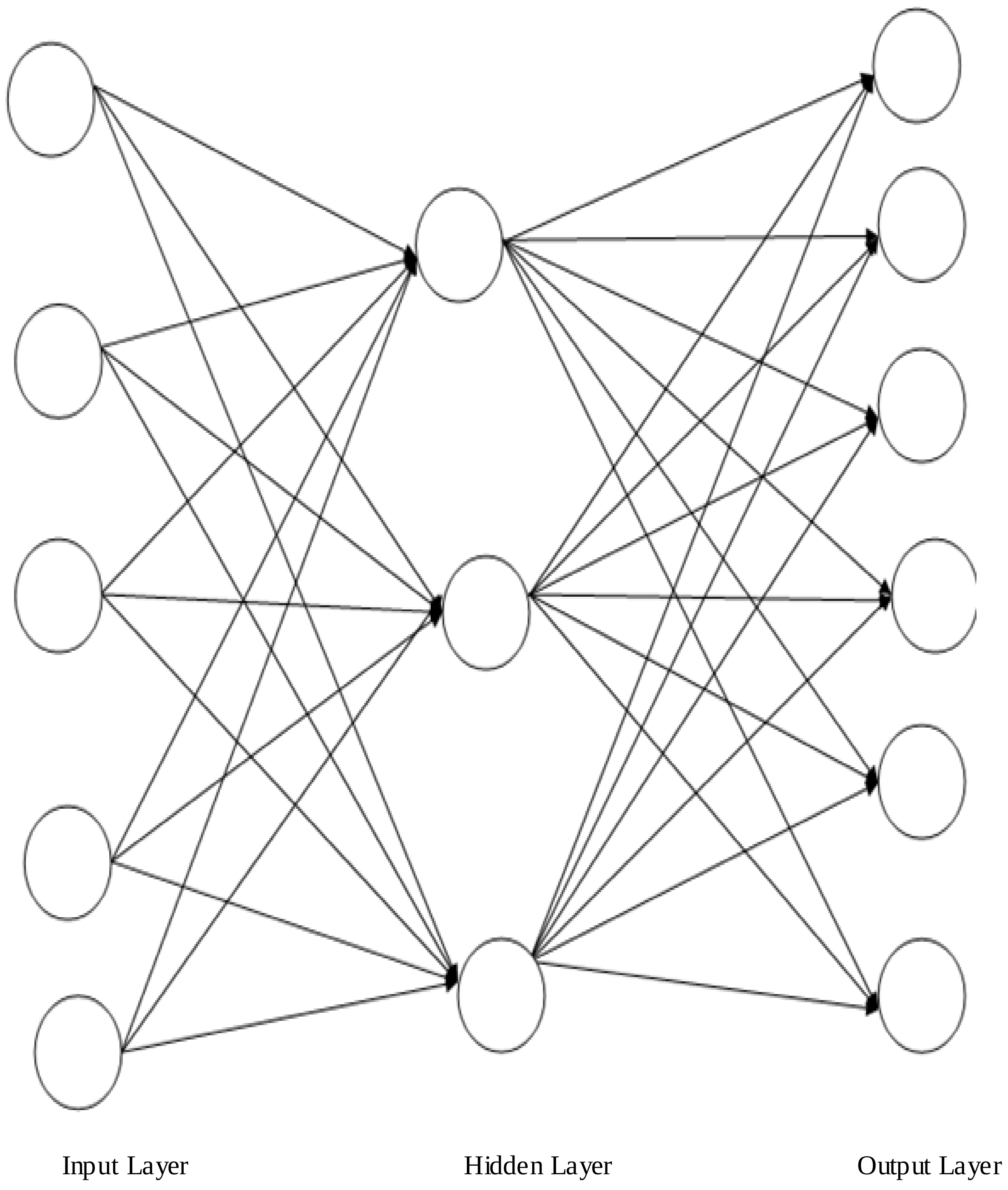


Fig. - 3.4: Optimum ANN – structure used in the present work

Table - 3.1: Shape/Size of samples selected for experimentation

Sl No.	Samples	Length (L) mm	Width (W) mm	Thickness (T) mm
1	Red kidney bean	10.25	5	5
2	Bean Seed	11	5.5	4.9
3	Wheat	4.2	2.2	1.75
4	Rice	3.2	2	1.5
5	Ladies Finger	63.42	20.14	18.29
6	Ivy gourd	70.18	24	21.05
7	String Beans	72.05	6.34	5.4

Table - 3.2: Shape/Size of soaked grains before drying

Sl No.	Samples	Length (L) mm	Width (W) mm	Thickness (T) mm
1	Red kidney bean	18	10.24	6.25
2	Bean	15.33	8.9	6.69
3	Wheat	6.78	4.33	3.98
4	Rice	5.9	4.12	3.15

Table - 3.3: Physical properties of selected grains and vegetables at room temperature before experiment

Sl No.	Samples	V (mm^3)	Sa (mm^2)	ϕ (%)	ρ_b (kg/m^3)	ρ_t (kg/m^3)	ε (%)
1	String Beans	672.325	689.428	18.713	180	255	0.29
2	Ladies Finger	7202.794	2251.727	44.925	445	500	0.11
3	Ivy gourd	11046.28	2948.734	46.647	690	1030	0.33
4	Wheat	38.563	58.931	69.233	825	1290.23	0.36
5	Rice	33.067	52.093	74.582	645.11	960	0.33
6	Bean Seed	288.097	228.695	65.811	931.52	1535	0.39
7	Red kidney bean	306.096	239.469	64.662	0.189	0.5	0.62

Table - 3.4: Scope of the experiment with the grains and pulses

Sl No.	Samples	ρ_s(kg/m^3)	t (min)	θ (^oC)	U_o (m/s)
1	Red kidney bean	1230	10	60	3.800
2	Red kidney bean	1230	20	60	3.800
3	Red kidney bean	1230	30	60	3.800
4	Red kidney bean	1230	40	60	3.800
5	Red kidney bean	1230	50	60	3.800
6	Red kidney bean	1230	50	40	3.800
7	Red kidney bean	1230	50	50	3.800
8	Red kidney bean	1230	50	60	2.875
9	Red kidney bean	1230	50	60	1.950
10	Red kidney bean	1230	50	60	0.975
11	Bean	1215	50	60	3.800
12	Wheat	1100	50	60	3.800
13	Rice	1357	50	60	3.800

Table - 3.5: Scope of the experiment with the Mushroom

Sl No.	Samples	L/D	t (min)	θ (^oC)	U_o (m/s)
1	Mushroom	0.628	10	50	3.800
2	Mushroom	0.628	20	50	3.800
3	Mushroom	0.628	30	50	3.800
4	Mushroom	0.628	40	50	3.800
5	Mushroom	0.628	50	50	3.800
6	Mushroom	0.628	50	40	3.800
7	Mushroom	0.628	50	60	3.800
8	Mushroom	0.628	50	70	3.800
9	Mushroom	0.628	50	50	2.875
10	Mushroom	0.628	50	50	1.950
11	Mushroom	0.628	50	50	0.975
12	Mushroom	0.89	50	50	3.800
13	Mushroom	1.2	50	50	3.800
14	Mushroom	1.6	50	50	3.800
15	Mushroom	5.2	50	50	3.800

Table - 3.6: Scope of the experiment with different vegetables

Sl No.	Samples	L/D	t (min)	θ (^oC)	U_o (m/s)
1	Ivy gourd (Tundli)	1.2	10	50	3.800
2	Ivy gourd (Tundli)	1.2	20	50	3.800
3	Ivy gourd (Tundli)	1.2	30	50	3.800
4	Ivy gourd (Tundli)	1.2	40	50	3.800
5	Ivy gourd (Tundli)	1.2	50	50	3.800
6	Ivy gourd (Tundli)	1.2	50	40	3.800
7	Ivy gourd (Tundli)	1.2	50	60	3.800
8	Ivy gourd (Tundli)	1.2	50	70	3.800
9	Ivy gourd (Tundli)	1.2	50	50	2.875
10	Ivy gourd (Tundli)	1.2	50	50	1.950
11	Ivy gourd (Tundli)	1.2	50	50	0.975
12	Ivy gourd (Tundli)	1.2	50	50	3.800
13	Ivy gourd (Tundli)	1.2	50	50	3.800
14	Ivy gourd (Tundli)	0.89	50	50	3.800
15	Radish	1.2	50	50	3.800
16	Ladies Finger	1.6	50	50	3.800
17	String Beans	5.2	50	50	3.800

Table -3.7: Used optimum ANN-parameters for three layered, Back Error Propagation type network

ANN-Parameters:	For M_C of grains	For M_C of vegetables	For D_{eff}. Of mushroom	For D_{eff}. of vegetables
Slope parameter (λ)	0.95	0.95	0.95	0.95
Learning-rate (α)	0.001	0.001	0.001	0.001
Number of training vectors	64	68	72	68
Number of testing patterns	80	84	90	84
Maximum Cycles/ epochs	25000	20000	20000	20000
No. Input nodes	05	05	05	05
No. of hidden nodes	03	03	03	03
No. Output nodes	06	06	06	06

Table - 3.8: Factors and levels used in the Taguchi analysis for experimental data

Factors	A	B	C
	t (min)	θ (^{o}C)	U_o (m/s)
Level 1	10	40	0.975
Level 2	20	50	1.95
Level 3	30	60	2.875
Level 4	40	70	3.8

Table - 3.9: Design of experiments using L16orthogonal array of Taguchi analysis

Trail No.	t(min)	θ(^{o}C)	Uo(m/s)
1	10	40	0.95
2	10	50	1.95
3	10	60	2.80
4	10	70	3.80
5	20	40	1.95
6	20	50	0.95
7	20	60	3.80
8	20	70	2.80
9	30	40	2.80
10	30	50	3.80
11	30	60	0.95
12	30	70	1.95
13	40	40	3.80
14	40	50	2.80
15	40	60	1.95
16	40	70	0.95

CHAPTER IV

RESULTS AND DISCUSSION

4.1. Introduction

Shape and size of agro materials vary with their moisture loss. Thus, shape and size of the products change appreciably with the moisture loss thereby influencing their physical properties which in turn modifies the final texture and transport properties of the dry products. Knowledge of physical and mechanical properties of various crops (seeds /grains) is essential in the design of equipment for handling, drying, aerating, storing structures and processing of the materials. A certain amount of moisture gets lost during the drying process that reduces the weight of the sample. This amount of moisture loss during drying is measured as the amount of mass transfer. Therefore, knowledge of mass transfer coefficients for crops can provide information about the quantity of moisture going to be lost under any particular condition without carrying out real experiments on drying. The prior information on moisture loss during drying under any condition can lead to a proper dryer design as per the actual requirement which in turn will be very much energy efficient. There is always demand for an economic or cost efficient drying operation that needs a more detailed study on the temperature dependence of mass transfer coefficients for different feed samples of the dryer.

The knowledge of physical properties of samples and how these properties get affected by the moisture loss is important for design of suitable equipments for handling, transporting, processing and storing the grains. Additionally, information on drying kinetics is necessary for design and prediction of dryer performance as drying is the most common preservation process applied to crops. Therefore, the purposes of the present work were to investigate the effects of moisture loss on different physical properties such as axial dimensions, volume, sphericity, internal porosity, true density and apparent density of agro materials.The evaluation of the drying kinetics of grains and vegetables under different drying conditions were planned to be carried out. A thin layer thickness is defined as the thickness meeting the drying requirement under different conditions (viz. temperature and relative humidity) of the drying air that do not change when passing through the grain layer [97]. These data can further be used to estimate the drying time.

In the present study, the drying performances of fluidized bed dryer were observed experimentally by varying different system parameters viz. temperature, time of drying, velocity of air and density/aspect ratio of the feed material. The drying characteristics of various samples such as grains and vegetables are studied through the moisture content-analysis of the samples. It is observed that removal of moisture is more with the sample whose initial moisture content is more.

An Artificial Neural Network analysis is used with a systematic, step-by-step procedure that optimizes a criterion. Neural Network also converts a nonlinear nature processing system to a very flexible system and optimizes a criterion by its learning rule. Moisture content and diffusivity of the samples are correlated against the system parameters on the basis of Dimensionless as well as ANN analysis. Further Taguchi analysis is used to design the experiments of drying with respect different aspects of drying i.e. efficiency of the dryer, moisture loss and diffusivity of the feed samples.

The analyses of all these aspects are discussed in details in the following sections. Results of all these parts are analyzed with different correlations, plots and data tables. Important plots such as drying curves of different samples and correlation plots along with their comparison plots for different aspects are discussed in this chapter while all other plots are listed in **Appendix-I** for references. All the observed data and calculated data in tabular form are shown in **Appendix-II.**

4.2. Drying Curves

During drying process, moisture contents of different samples are noted at 10 minutes interval of time. It is observed that moisture content of samples decrease with time. The drying curves for different agro-materials are plotted in Fig. - 4.1

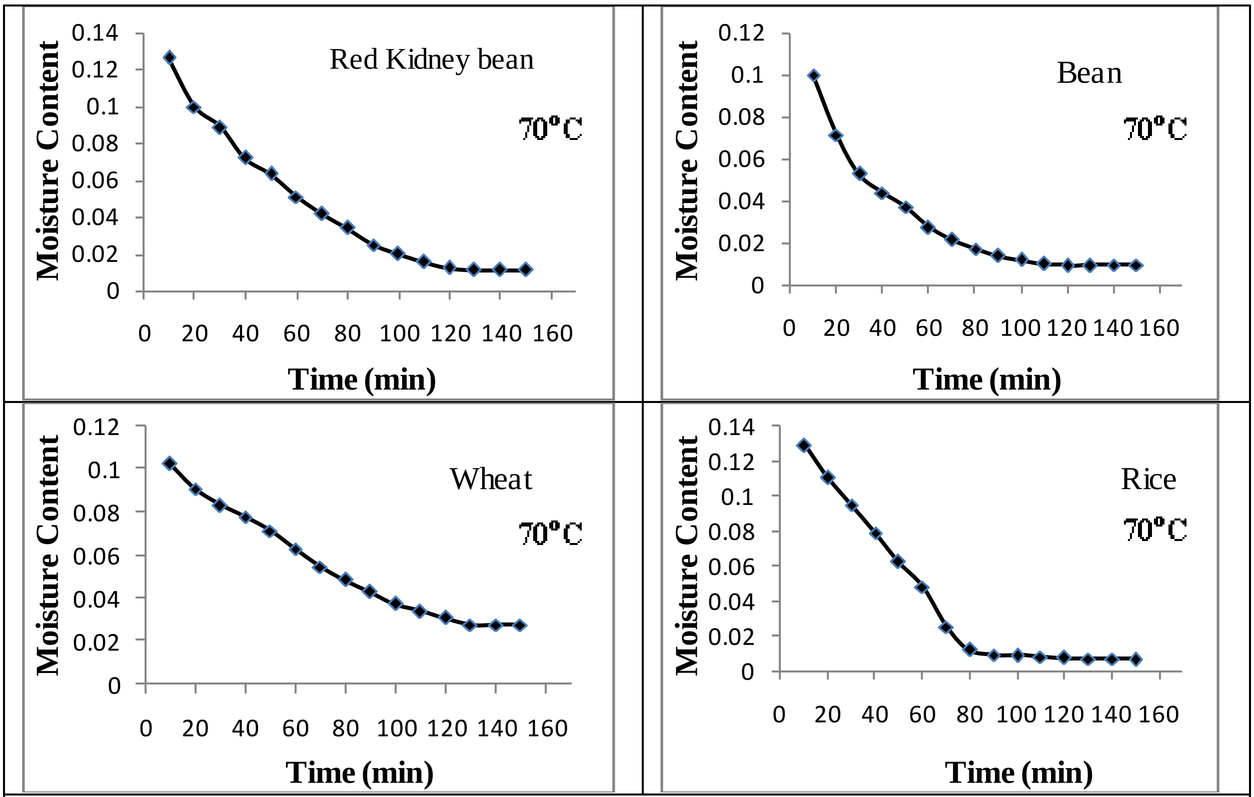


Fig. - 4.1 (A): Drying curves for different grains

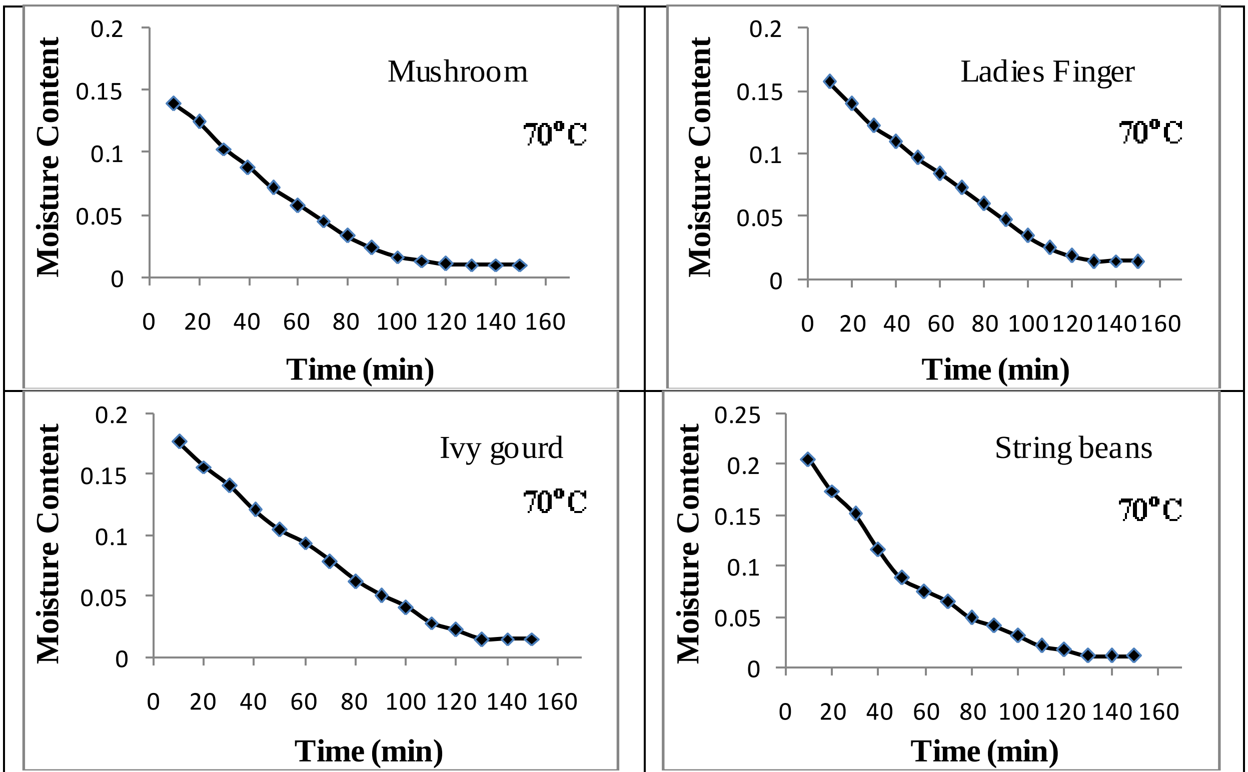


Fig. - 4.1 (B): Drying curves for different vegetables

From all these figures it is observed that drying occurs mostly in the falling rate period for both grains and vegetables. In all these figures it is also seen that rate of drying is constant occurs at around 130 minutes and continues up to around 150 minutes of drying from beginning. Short constant period of drying confirms that the feed samples initially contain surface moisture. It is well known that crops (grains and vegetables) contain initial surface moisture. Since crops are considered as the feed samples it can be said that the above drying curves showing short constant rate period are justified.

4.3. Moisture Loss and Shrinkage Aspects

Moisture loss of different grains and vegetables are analysed during drying in a fluidized bed dryer. Information about the drying characteristics of the samples under any particular condition is obtained from moisture loss of the sample. The drying characteristics are expressed in terms of the moisture loss of the sample on the basis of regression analysis by correlating the experimentally observed moisture loss of the sample against the different system parameters.

Finally correlations are developed by two approaches namely, Regression analysis and Artificial Neural Network analysis. The experimentally observed dependent variable i.e. moisture loss along with the different independent system parameters for grains and vegetables are listed in Appendix-II (Table - 1 & 2). The effects of individual parameters on the moisture loss of the samples for grains and vegetables are shown in Appendix-I (Fig. - 1 & 2 respectively). The respective correlation plots are shown in Fig. - 4.2 & 4.3. Plots showing comparison between experimentally observed and calculated data for both grains and vegetables are shown in Fig. - 4.4 & 4.5. The final correlations for the moisture loss of different crops developed on the basis of regression analysis are mentioned below.

For grains:

$$M_L = 1512 * \left[\left(\frac{t}{t_{\max}} \right)^{-0.98} \left(\frac{\theta}{\theta_{\max}} \right)^{-2.944} \left(\frac{U_o}{U_{\max}} \right)^{-0.453} \left(\frac{\rho_s}{\rho_f} \right)^{-1.65} \right]^{1.0232} \tag{4.1}$$

For vegetables:

$$M_L = 0.111 * \left[\left(\frac{t}{t_{\max}} \right)^{-0.049} \left(\frac{\theta}{\theta_{\max c}} \right)^{-3.652} \left(\frac{U_o}{U_{\max}} \right)^{-0.74} \left(\frac{L}{D} \right)^{-1.17} \right]^{0.68} \tag{4.2}$$

It is observed from the figures Fig. - 4.2 & 4.3 and the above correlations (Eq. - 4.1 & 4.2) that the moisture loss of samples decrease with the increase in each parameter for both the grains and vegetables indicating that drying (evaporation of moisture from samples) is directly related to each of these parameters. This is so happend because with increased contact time, hot air is allowed to be in contact with surface of particle for more time. Similary, with increased temperature more water evaporates from the surface and with increased air velocity more and more hot air comes in contact with particle surface. As a result, more moisture is evaporated from the feed. In other words, it can be said that the drying efficiency increases with increase in each of the system parameters studied for both grains and vegetables. The high value of R^2 for the correlation plot shows that the correlation fit is proper in both the cases.

The variation of volume ratio (V_R) and moisture ratio (M_R) for different samples are observed with time as shown in Appendix-II (Table - 3, 4, 5 6, 7, 8, & 9). The shrinkage (change in volume ratio) against time of drying is also studied for grains and vegetables with different aspect ratios (L/D ratios) and shapes of samples. The moisture ratio (M_R) and volume ratios (V_R) are calculated for various samples as per the Eq. - 2.7 & 2.27. Sample plots of moisture ratio, volume ratio against time for different crops with different shapes are shown in Fig. - 4.6, 4.7, 4.8 & 4.9. It is observed that the moisture ratio increases and volume ratio decreases with the increase in time for all the samples which is true because volume ratio is defined as the ratio of volumes of sample after and before drying. After drying, volume decreases as more moisture is removed with time. That means the decreased volume after drying which is in the numerator of the ratio causes V_R to decrease further with time indicating less volume ratio.

It is also observed from Fig. - 4.7 that the moisture ratio is less for pentagonal shaped crops (ladies finger) than for cylindrical shaped sample (ivy gourd). In Fig. - 4.9 volume ratio is seen to be less for pentagonal shaped sample and more for cylindrical shaped sample (string beans) indicating more moisture is removed from the cylindrical shaped surface because more surfaces are exposed to the drying medium due to the curved surfaces. For cylindrical shape, surface area is πDH, with unit height it is πD. For pentagonal shape, surface area is product of perimeter and height. Thus with unit height it is only perimeter which is sum of its five sides. As with same size, circle perimeter is more than perimeter of inscrived pentagon. Therefore cylindrical shape has more surface area than that of a pentagon. This implies that drying is better for cylindrical shaped crops than for pentagonal shaped crops of approximateliy same size.

It is observed that the shrinkage is not a homogenous phenomenon. Change in volume and shape are different for different aspect ratios (L: D). During the initial stage of drying, String beans and Ivy gourd retain their smooth surface and shape although some reduction in volume is observed (Fig. - 4.7).

This may be due to the fact that very less moisture contents might have evaporated during the initial stage. But after certain time it is observed that Ivy gourd shows more moisture ratio than String bean and Ladies finger which may be due to more initial moisture loss of the sample for its higher thickness. Again after 40 mins of drying time, all samples show same moisture ratio indicating attainment of constant period of drying. Wheat sample shows more moisture ratio than other grains in Fig. - 4.6. Initially Red kidney bean and Rice afterwards show less moisture ratio. Reason may be inferred to the cracked structure of Wheat crops for retaining more surface moisture thereby showing more moisture ratio. Again all grains show same moisture ratio after 40 mins of drying. Same reason as for vegetables may be applied to grains (i.e. attainment of constant period of drying). From Fig. - 4.8 it is seen that Red kidney bean shows more volume ratio and Wheat sample shows less volume ratio. This may be due to the fact that surface area difference, before and after drying might be more for Red kidney bean than Wheat. From Fig. - 4.9 it is seen that higher thickness of Ivy gourd causes less shrinkage leading to less volume ratio than String bean and Ladies finger.

The variation of volume ratios (V_R) are plotted against the moisture ratios (M_R) for samples with different shapes in Fig. - 4.10 & 4.11 respectively. It is observed that the volume ratio decreases with increase in moisture ratio for all the samples. This may be due to the fact that rtemoval of more moisture causes shrinkage in the sample for which there is reduction in the volume after drying. Thats why volume ratio decreases with removal of more moisture from the sample.

The drying constants and shrinkage constants are determined from these correlations. The observed data are correlated exponentially as per Eq. - 2.9 and listed in Appendix II (Table - 10) with their drying and shrinkage constants. It is observed that the shrinkage constant and drying constant for the pentagonal shape (Ladies finger) are more in comparison with the other shapes. For grains, it is observed that Red kidney bean is showing higher drying and shrinkage constants in comparison with the other samples (Appendix II, Table - 10). This may be due to increased M_R and V_R for the decreased contact area with the drying medium for the Red kidney bean and Ladies finger. Thus, it can be said that drying constant and shrinkage constants indicate the resistances for drying.

For ANN learning a set of training data is prepared by considering all experimental observations. Another data set is prepared for testing the results. Calculated values of moisture contents obtained through Eq. - 4.1 & 4.2 are used as target data set. Network performances are evaluated by comparing the output of ANN training against those of target data and analyzing the root mean square (RMS) error between the normalized and target data over 5000 to 20000 number of epoches or cycles.The numbers of neurons in this hidden layer are varied to find the structure that provides the least error and thus the optimum ANN – structure (Fig. - 3.3) is determined. The different ANN-parameters for three layered, Back Error Propagation type network are given in Table - 3.7. Finally all output parameters are determined for ANN-modelling. Using all these output data the correlations are developed. The calculated values of moisture loss thus obtained are compared against the experimentally observed values and root mean square (RMS) error are calculated. The plots of RMS error against the number of cycles or epochs for both the grains and vegetables are shown in Fig. - 4.12 & 4.13 respectively. The weights of ANN learning are shown in Appendix III steadiness in weights also confirms proper training of ANN-learning. Using the output data obtained with optimum ANN structure, the correlations are developed for both the grains and vegetables which are shown below.

For grains:

$$M_L = 12190 * \left[\left(\frac{t}{t_{\max}} \right)^{0.93} \left(\frac{\theta}{\theta_{\max}} \right)^{1.14} \left(\frac{U_o}{U_{\max}} \right)^{1.03} \left(\frac{\rho_s}{\rho_f} \right)^{1.03} \right]^{1.05} \tag{4.3}$$

For vegetables:

$$M_L = 103.99 * \left[\left(\frac{t}{t_{\max}} \right)^{0.45} \left(\frac{\theta}{\theta_{\max}} \right)^{0.44} \left(\frac{U_o}{U_{\max}} \right)^{0.44} \left(\frac{L}{D} \right)^{0.43} \right]^{0.51} \tag{4.4}$$

It is observed from the RMS error plot for grains (Fig. - 4.12) that error changes from 0.24 at 00 numbers of cycles to 0.00 at 140 numbers of cycles. The error did not change further; RMS error remained constant over 25000 numbers of cycles. RMS error for vegetables (Fig. - 4.13) started at 0.24 decreased to 0.1 at 5000 number of cycles and remained constant over 20000 cycles. This constant nature of error over a wide range of cycles implies that training is proper. The outputs for optimum structure thus obtained are listed in Appendix II (Table - 11).

Finally, the calculated values of the moisture-loss for different grains and vegetables obtained by both the methods are compared with the experimentally observed values. The exponents of parameters and correlation coefficients for both the methods are listed in Appendix II (Table - 11). The standard and mean deviations for these measurements are listed in Appendix II (Table - 12). The correlation coefficient (R^2), chi-square (χ^2) for these expressions are calculated and listed in Appendix II (Table - 12). Small values of deviations indicate that the developed correlations can be used over a wide range of parameters. The low value of standard and mean deviation for ANN approach indicates very good validation of the expression developed by the Regression Analysis approach. Again low value of R^2 for grains-correlation indicates better correlation fit than that of vegetables. The mass transfer coefficients (K) for different samples subjected to fluidized bed drying are also calculated using moisture loss data. The obtained K-values are ploted against the temperature to get the mass transfer equations for different grains and vegetables which are listed in Appendix II (Table - 13).This implies drying rate or removal of moisture loss is more for mushroom than for grains.

It is observed that there is a relation between volume reduction and drying constant during drying which further depends on the shape or size and structure of the material. Thus, information on shape and structure of feed sample can be useful to know the requirement for drying intensity beforehand which will minimize the energy requirement to much extent.

Low values of the standard and mean deviations confirm the validity of the developed correlations thereby implying their uses over a wide range of parameters.

Mainly the temperature parameter is found to control the drying rate significantly where the drying time is also controlled. As the drying time is a function of the moisture loss of sample, increase in drying air temperature decreases the drying time. The drying process is observed to occur in both falling rate and constant rate periods.

The very good agreement between ANN-model and experimental data proves that the training of ANN learning is proper. Based on the results of the error analysis, it is found out that the neural network with the selected neurons and the transfer function with back propagation algorithm are appropriate to ANN configuration for purpose of drying time prediction. The selected ANN model successfully learned the relationship between the input parameters and output parameters.

4.4. Diffusivity of Samples

During drying, internal moisture of particles moves towards the surface because of diffusion. Then it evaporates and passes on by convection to the surroundings. Therefore, there is a need to calculate the moisture diffusivity to understand the drying process properly.

Attempt has been made to study the diffusivity of mushroom and different vegetables (viz. Radish, Ivy gourd, Ladies finger and String beans (Barbatti, one type of local Beans) dried through a fluidized bed drier in the present study. Fick's diffusion equation has been used for the calculation of effective moisture diffusivity of samples. The drying characteristics in terms of diffusivity of the sample are expressed by correlating the observed diffusivity of the sample with the different system parameters for both, the mushroom and vegetables. The developed correlations are as given below.

For Mushrooms:

$$D_{eff} = 0.013 * \left[(t)^{-1.13} (\theta)^{-0.52} (U_o)^{0.109} \left(\frac{L}{D} \right)^{-3.35} \right]^{0.798} \quad (4.5)$$

For Vegetables:

$$D_{eff} = 0.358 * \left[(t)^{-1.33} (\theta)^{-0.72} (U_o)^{-0.35} \left(\frac{L}{D} \right)^{-2.65} \right]^{0.982} \quad (4.6)$$

The experimentally observed dependent variable i.e. diffusivity along with the different independent system parameters are listed in Appendix II (Table - 14 &15) for mushroom and vegetables respectively. The effects of individual parameters on the diffusivity of the samples are shown in Appendix I (Fig. - 3 & 4) for Mushroom and vegetables respectively. It is observed from the exponents of the correlations that increased velocity of the air increases the diffusivity of Mushroom Appendix I (Fig. - 4 (C)) whereas all other parameters have inverse effects on diffusivity of the samples for both, mushrooms and vegetables. Increased velocity is also observed to decrease the diffusivity of the vegetables Appendix I (Fig. - 4(C)).

The correlation plots for diffusivity of the samples against the system parameters are shown in Fig. - 4.14 & 4.15 for mushrooms and vegetables respectively. Comparison plots are shown in Fig. -

4.16 & 4.17 for mushroom and vegetables. As a whole it is observed that the diffusivity of the samples increases with the increased variation of the system parameters as the overall exponents are found to be positive for both the cases, i.e. for Mushroom and vegetables.

ANN-learning is also used for diffusivity correlations. Thus the developed correlations for diffusivity through ANN-learning are written as follows.

For Mushrooms:

$$D_{eff} = 0.07 * \left[(t)^{1.33} (\theta)^{0.72} (U_o)^{0.32} \left(\frac{L}{D} \right)^{2.65} \right]^{0.85} \quad (4.7)$$

For Vegetables:

$$D_{eff} = 0.28 * \left[(t)^{1.15} (\theta)^{0.08} (U_o)^{0.36} \left(\frac{L}{D} \right)^{1.75} \right]^{0.98} \quad (4.8)$$

The calculated values of effective moisture diffusivity thus obtained are compared against the experimentally observed values and root mean square (RMS) errors are calculated. The plots of RMS error against the number of cycles or epochs for both, the mushroom and vegetables are shown in Fig. - 4.18 & 4.19 respectively.

It is observed that the RMS error for vegetables (Fig. - 4.18) is almost negligible in comparison with the Mushrooms. RMS error for Mushrooms (Fig. - 4.19) starts from 0.35 at 0 numbers of epoch and decreases to 0.17 at 100 numbers of epochs which remains constant over 20000 numbers of epochs. RMS error for vegetables starts from 0.25 at 0 number epoch and falls to 0.001 at 100 numbers of epochs which remains constant over 20000 numbers of epochs.

Correlations are developed for the drying characteristics in terms of the diffusivity of the vegetables by relating the experimentally observed values of the diffusivity of the sample against the different system parameters. The calculated values of the diffusivity of different vegetables and mushrooms are compared with the experimentally observed values.

The drying characteristic, diffusivity of the samples are calculated by using both Regression and Artificial Neural Network analysis and listed in Appendix II (Table - 14 & 15). The comparisons of calculated values of diffusivity with experimentally observed values are made in Appendix II (Table - 14 & 15) for mushrooms and vegetables respectively.

Thus the effective moisture diffusivity, D_{eff} is calculated using the slopes for drying curves and Eq. - 2.11. The calculated values of effective moisture diffusivity for different samples are listed in Appendix II (Table - 16). The time of drying is observed to affect the effective moisture diffusivity of mushroom and other vegetables. It is observed that the moisture diffusivity decreases with the increase in drying time.

Activation energies for different samples are calculated using the Arrhenius expression i.e. Eq. - 2.12 and listed in Appendix II (Table - 17). It is observed that during the initial stage of drying, vegetables have registered the highest activation energy at different drying temperatures. It is also observed that the activation energy increases with increase in time for Mushroom and Ivy gourd. It is further evident from Appendix II (Table - 17) that vegetables require minimum activation energy to detach and move the water molecules during the drying process.

The calculated values of moisture content and effective moisture diffusivity of grains/mushrooms and other vegetables are compared with each other and with their experimental values. The standard and mean deviations of these measurements are listed in Appendix II (Table - 18). These values indicate that the developed correlations are proper and can be used over a wide range of parameters. The very low value of standard and mean deviations for ANN approach indicates very good validation of the Regression Analysis approach. The outputs of the ANN-model (a, b, c, d, K', n) for both the moisture-loss content and diffusivity of different grains and vegetables are compared with the outputs obtained through the Regression Analysis as shown in Appendix II (Table - 19). The mass transfer coefficients for different samples subjected to fluidized bed drying are also calculated and plotted against the temperature to get the mass transfer kinetics for different vegetables (Appendix II, Table - 20).

The performance of fluidized bed drier is studied by analyzing diffusivity of the sample during drying operation. Attempts are also made to develop correlations for these drying performances of the fluidized bed dryer on the basis of Regression Analysis which further are validated by Artificial Neural Network approach. As the standard and mean deviations obtained by comparison with the experimental values are very low, the validity of the correlation can be considered to be very good. Therefore, the developed correlations can be recommended to be used in a wide range of conditions. Heat transfer and mass transfer along with their kinetics are also analyzed during drying of different samples in the present study.

Drying kinetics for mushroom and vegetables are also observed through the measurement of activation energy and mass transfer coefficients. Knowledge of activation energy which can minimize the wastage of energy during drying is of great help for optimization of the process.

The coefficients of the developed models and the apparent diffusion coefficients are the most important parameters for the transferring of moisture. These were also found to be dependent on the temperature and velocity of the drying air. The effect of temperature on the diffusivity is expressed by the Arrhenius equation where the logarithm of the diffusivity exhibited a linear behaviour against the reciprocal of the absolute temperature.

ANN-model and experimental data prove that the neural network training is proper and it fits well with the behaviour of the different parameters. Based on the error analysis results, it is also found that the neural network with the selected neurons and the transfer function with back propagation algorithm are the most appropriate ANN configuration for the prediction of drying time. The selected ANN model successfully learned the relationship between the input and output parameters.

4.5. Mass Transfer Aspects for Different Crops

Movement of internal moisture from the inside of the particle to the particle surface takes place by diffusion. This transport of moisture is quantified by analyzing mass transfer coefficients. There is always a constant demand for an economic or cost efficient drying operation that requires a more detailed study on the temperature dependence of mass transfer coefficients for different feed samples of the dryer.

In the present study, different grains (viz. Red kidney beans locally known as Rajma, Bean seed, raw Rice, and Wheat) and various vegetables (viz. Radish, Ivy gourd, Ladies finger and String beans) are used as bed materials to study the mass transfer coefficient of the samples in a fluidized bed dryer. Sherwood number (*S*h), related to Schmidt and Reynolds numbers (Eq. - 2.18) is used for the calculation of effective mass transfer coefficient of the feed samples. Reynolds Number, Schmidt Number, Sherwood Number, effective diffusivity (D_{eff}) and thereby mass transfer coefficients at different drying temperatures are calculated using the equations from Eq. - 2.15 to 2.19. These values thus calculated for various grains and vegetables are tabulated in Appendix II (Tables - 21 & 22) respectively.

An attempt is further made to develop an expression for the mass transfer coefficient for the feed sample. The mass transfer coefficient thus obtained (as per Eq. - 2.19) are correlated with different system parameters on the basis of regression analysis for both grains and vegetables. The developed correlations are as follows.

For grains:

$$K = 0.0005 * \left[\left(\frac{t}{t_{\max}} \right)^{0.491} \left(\frac{\theta}{\theta_{\max}} \right)^{0.876} \left(\frac{U_o}{U_{o\max}} \right)^{0.816} \left(\frac{\rho_s}{\rho_f} \right)^{1.494} \right]^{0.866} \quad (4.9)$$

For vegetables:

$$K = 0.0115 * \left[\left(\frac{t}{t_{\max}} \right)^{0.562} \left(\frac{\theta}{\theta_{\max}} \right)^{1.501} \left(\frac{U_o}{U_{o\max}} \right)^{1.309} \left(\frac{L}{D} \right)^{1.494} \right]^{1.0064} \quad (4.10)$$

The effects of the individual parameter on mass transfer coefficients of the samples are shown in Appendix I (Fig. - 5 & 6). The correlation plots are shown in Fig. - 4.20 & 4.21 for grains and vegetables respectively. The values of the mass transfer coefficients obtained through the Eq. - 4.9 & 4.10 are compared with the values available in the literature (as per Eq. - 2.18) for different grains and vegetables. The comparisons of calculated values against experimental values of mass transfer coefficients along with the system parameters are shown in Appendix II (Table - 23).

From Fig. - 4.20 & 4.21 as well as from Eq. - 4.9 & 4.10 it is seen that all the system parameters have positive impact on the mass transfer coefficient. The reason may be same as explained in the section - 4.1, that means more surface moisture is removed with increasing effects of system parameters. From Eq. - 4.9 & 4.10 it is seen that overall exponents are positive. This implies that system parameters affect the mass transfer coefficients positively. The comparison plot shows a very good agreement.

The drying process of agro-materials mostly occurs in the falling rate period, and internal diffusion controls moisture transfer during drying. Flick's second law of diffusion, as shown in Eq. - 2.12 is widely used to measure the diffusivity of the samples. The primary assumption in determining the effective moisture diffusivity experimentally is that the process of drying is mass transfer controlled. Fick's law of diffusion (Eq. - 2.12) assumes that the moisture diffuses from the inside of the particle to the surface and evaporates at the surface. The fluidized beds are considered as perfectly mixed beds and the solids at any point in the beds are exposed to same drying conditions.

The mass transfer coefficient (K) is calculated based on correlations reported in the literature. The Sherwood number is the ratio of external mass transfer resistance to the molecular diffusivity. The effective diffusivity is estimated by minimizing the error between the experimental data. The estimated diffusivity coefficients are listed in Appendix II (Table - 21 & 22). It is seen from these tables that the effective diffusion coefficient increases with the reduction in solids holdup. The variation of diffusivity coefficient with solids holdup may be due to the following facts.

The temperature of the bed at any given time during the drying is found to be higher at a lower solid holdup as compared to drying with higher solid holdup because heat given up by air is gained by feed solid. Thus lesser solid will be heated to a higher temperature. Again, the reason for the higher drying rate with lower solid holdup is possibly explained. As some solids decreases, the amount of moisture that diffuses from the solids to the gas phase becomes less in quantity resulting in a higher bed temperature. The larger bed temperature increases the drying rate thereby indirectly increasing the rate of diffusion of moisture. The bed temperature varies from a value close to the wet bulb temperature to the inlet temperature of the drying medium. Although there is variation in the diffusion of moisture from the particles, the model predicts only a single average constant diffusivity for the entire period of drying. The drying process is affected by the internal moisture diffusivities for which the mass transfer coefficient varies. Therefore, differences between observed and calculated values for mass transfer coefficients are resulted. The increase in temperature causes the increase in the effective diffusion coefficient while mass transfer coefficient increases linearly.

Mass transfer coefficient in a fluidized bed dryer is determined experimentally. Comparison of the measured and calculated values of mass transfer coefficients is observed to show a reasonable agreement. The experimental findings with the varied mass transfer coefficients, K confirm the influences of several parameters

The drying of samples in a fluidized bed dryer mainly takes place as a result of moisture transfer from the dense solid phase. In this study, the mass transfer coefficient is estimated from experimental measurements at the drying air condition. The results are validated against the developed empirical correlations and for assessing the various assumptions used in developing these relationships. Despite the complexity of the process and the number of assumption employed in this analysis, diffusion mass transfer seems to provide satisfactory agreement with the experimental measurements.

4.6. Effects of Physical Properties of Feed Samples

Knowledge of physical and mechanical properties of feed samples (seeds /grains) is essential in the design of equipment for handling, drying, aerating, storing structures and processing of the materials. Shape and size of seed vary with its moisture content. Recently scientists have made great efforts in evaluating basic physical properties of agricultural materials with their practical utility in the machine and structural design and control engineering [48]**.** Recent scientific developments through mechanical, thermal, electrical, optical and other techniques have improved the handling and processing of biomaterials [49]. However, very little information is known about the underlying physical characteristics of agromaterials. Such basic information is very essential to professionals and scientist. In the present work different grains and vegetables are selected to investigate their physical properties using a fluidized bed dryer. Effects of the physical properties and system parameters on the efficiency of the dryer with respect to grains and vegetables are studied in the following sections.

4.6.1. With respect to *grains:*

The axial dimensions along with various other physical properties of feed samples measured at different levels of moisture loss during drying are listed in Appendix II (Table - 24, 25, 26, & 27). The axial dimensions of feed samples are found to decrease linearly with the increase in moisture loss of the samples during drying process. The reduction in these dimensions may be attributed to contraction of the samples because of moisture uptake in the intracellular spaces within the samples. The decrease in linear dimensions may be due to the fact that removal of moisture loss from the sample forces the samples to shrink linearly or axially. As a result, the effective diameter of the sample is found to be higher than the thickness of the samples after drying.

The values of sphericity (Φ) at different moisture levels are observed to decrease with the increase in moisture loss from the samples. The sphericity of different samples is found to be affected by moisture loss indicating that different samples might behave differently with respect to the relative changes in length, width and thickness that could affect sphericity. The sphericity (Φ) of Wheat is observed to be higher than the values reported for Bean seed / other grain samples. The high value of sphericity indicates that wheat might be expected to roll rather slide on the surface in comparison with the other samples. Thus, it can be said that this property (sphericity) is quite important in the design of grain hoppers.

The bulk and actual densities of samples are found to increase with an increase in moisture loss. The reason may be due to the fact that solid mass remains unchanged but net weight of sample decreases during drying. Thus, volume of sample drops which results increase in density. The relative expansion of the densities at lower moisture loss could be attributed to higher weight gain due to the reduced moisture about the concomitant volumetric reduction of the samples. It can be cited as the cause of the increase in both the bulk and actual densities. This increase indicates that as moisture content decreases, an increase in grain mass becomes higher in comparison with the decline in volume. Bulk / real density increases in either of two cases; i.e. when grain weight increases or volume reduction increases. The volumetric reduction of the sample and pore spaces becomes proportionally greater during drying that results in an increase in the bulk density.

But the actual densities of Red kidney beans (Rajma) and rice grains are observed to decrease with increase in moisture loss. The relative reduction in the densities of lower moisture loss could be attributed to less weight gain due to the reduced moisture about the concomitant volumetric expansion of the grains.

Porosity (ε) is calculated using the bulk density and actual density of the samples. The porosity is found to decrease linearly with an increase in moisture level. Higher porosity provides better aeration and water vapor-diffusion during deep bed drying. Lower porosity indicates lesser aeration and water vapor-diffusion.

When the bulk density increases, the decrease in porosity is resulted. Or, with relatively higher expansion in actual density, the porosity decreases. The porosity of different samples responds differently to changes in the moisture loss that could be attributed to their morphological characteristics.

The efficiency of the fluidized bed dryer is calculated as per Eq. - 2.10. The thermal efficiency of the dryer thus calculated for different grains at different levels of moisture loss are tabulated in Appendix II (Table - 28). The effects of the different individual parameters and different physical properties on efficiency of the samples are shown in Appendix I (Fig- 7 & 8).

Two correlations are thus developed for drying efficiency on the basis of regression analysis using the different physical properties and system parameters respectively. The respective correlation plots are shown in Fig. - 4.22 & 4.23. These correlations are expressed as follows.

$$\eta_1 = 0.562 * \left[\left(\frac{t}{t_{\max}} \right)^{0.319} \left(\frac{\theta}{\theta_{\max}} \right)^{0.482} \left(\frac{U_o}{U_{\max}} \right)^{0.085} \left(\frac{\rho_s}{\rho_f} \right)^{0.914} \right]^{0.336} \tag{4.11}$$

$$\eta_2 = 4.057 * \left[(V)^{0.068} (S_a)^{0.105} (\phi)^{1.134} (\rho_b)^{0.476} (\rho_t)^{0.247} (\varepsilon)^{0.43} \right]^{0.772} \tag{4.12}$$

From equation - 4.11 it is observed that efficiency is mostly affected by density parameter although all other parameters are found to have positive effects.

From equation - 4.12 it is seen that the effect of sphericity on efficiency is more significant in comparison with other physical properties although other physical properties are also found to affect the dryer efficiency. It is further reported in literature [98] that with increase in roundness flow index of particles increases. During drying as the moisture content in the sample decreases the roundness or sphericity of the material increases. Thus flow ability of feed material increases which thus facilitates the fluidization operation. Therefore efficiency improves thereby reducing energy requirement.

High values of R^2 in these figures (Fig. - 4.22 & 4.23) confirm that the correlation fits are proper. It is also observed that the moisture loss of sample decreases or drying rate increases with the rise in each of the system parameters. Efficiencies of the dryer calculated with physical properties and system parameters (as per Eq. - 4.11 & 4.12) are compared against the efficiencies calculated as per

Eq. - 2.10 (as reported in the chapter II). A comparison data table and plot are shown in Appendix II (Table - 28) & Fig. - 4.24 respectively.

The mean and standard deviations for the efficiency of the samples measured at different levels of moisture are listed in Appendix II (Table - 29). The correlation coefficient (R^2), chi-square (χ^2) for these correlations are calculated and listed in Appendix II (Table - 29). These values indicate that the developed correlations are comparable with the equation available in the literature. Therefore, these expressions can be used over a wide range of parameters. The small values of standard and mean deviations for the developed correlations validate them against the expression available in literature and also against the experimentally observed data.

4.6.2. With respect to *vegetables*

The correlations for the dryer efficiency are also developed on the basis of regression analysis using different vegetables (Ladies finger, Ivy gourd and String beans). The effects of system parameters and physical properties on efficiency of dryer are analysed in this section as per the following. These correlations are expressed as follows.

$$\eta_1. = 11.73 * \left[\left(\frac{t}{t_{\max}}\right)^{0.084} \left(\frac{\theta}{\theta_{\max}}\right)^{0.648} \left(\frac{U_o}{U_{\max}}\right)^{0.164} \left(\frac{\rho_s}{\rho_f}\right)^{0.165} \right]^{2.207} \tag{4.13}$$

$$\eta_2 = 5.858 * \left[(V)^{0.34} (S_a)^{0.34} (\phi)^{0.504} (\rho_b)^{0.416} (\rho_t)^{0.550} (\varepsilon)^{0.334} \right]^{0.759} \tag{4.14}$$

The experimentally observed data on efficiency along with the various system parameters are listed in Appendix II (Table - 33). The effects of individual parameters on the efficiency of the dryer are also studied and plotted (Appendix I, Fig. - 9) & it is observed from these plots and the correlation (Eq. - 4.13) that time, temperature of drying, velocity of hot air and density of sample have positive effects on dryer efficiency. However temperature effect is seen to be more significant. It is obvious that with increase in temperature more moisture is removed which increases the dryer efficiency.

Similarly the experimentally observed data on efficiency along with the various physical properties are listed in Appendix II (Table - 33). The effects of individual physical properties on efficiency are shown in Appendix I (Fig. - 10) and Eq. - 4.14. From this Fig. - 10 and correlation Eq. - 4.14 it is observed that all the physical properties have positive effects on dryer efficiency. However, effect of density is observed to be more significant in comparison with the other properties. Reason may be due to the fact that different vegetables are of different shapes which might be affecting the flow properties due to their surface irregularities. That is why more dense material may be flowing better where other factors are not significant. The respective correlation and comparison plots are shown in Fig. - 4.25, 4.26 and Fig. - 4.27.

It is observed that efficiency of the dryer increases or drying increases with the increase in both, the system parameters and the physical properties of the samples. High values of R^2 indicate that the developments of correlations are proper. Finally, the calculated values of the efficiency are compared with the experimentally observed values.

The axial dimensions of the samples at different levels of moisture are listed in Appendix II (Table - 30, 31 & 32). Each principal dimension appeared to be linearly dependent on moisture loss. The standard and mean deviations for the efficiencies are listed in Appendix II (Table - 34). Correlation coefficient (R^2), chi-square (χ^2) for these expressions are calculated and listed in Appendix II (Table - 34). These deviations indicate that the developed correlations can be used over a wide range of parameters. The low values of standard and mean deviation for efficiencies indicate very good validation of the developed correlations**.**

The physical properties of different samples are observed under different conditions of drying. The results thus obtained from this study can be helpful for the design of storage and packing equipments. Therefore storage unit can be designed properly so that materials will not damage and can be used whenever required. This observed data can also help during the preservation of food in food industry.

The Taguchi method is mainly used to design the experiments and effectively reduces the number of experimental trials. The control factors in this method as shown in Table - 3.8 include different levels of drying time, temperature and air velocity during the drying process.

In the present drying system three operating parameters, each at four levels, are selected to evaluate the drying characteristics for different samples. The factors to be studied are mentioned in Table - 3.8. Based on Taguchi method, the L16 orthogonal array (OA) is constructed. L16 orthogonal array (OA) is used to evaluate the significance of interaction terms. Interaction means the influence of an operating variable on the effect of other operating variables. The fractional factorial designs used for L16 orthogonal array with four levels and three factors are shown in Table - 3.9. Levels for each factor in the matrix are represented by '0'; '1' '2' and '3' where '0' is the minimum value and '3' is the maximum value.

Results of the L16 orthogonal array for producing different samples on the drying process are shown in Appendix II (Table - 35 – 38). The S/N ratio is calculated from the average experimental data at a moisture level for the dryer performance (Eq. 2.26) and shown in Appendix II (Table - 35 – 38). Regardless of the category of the performance characteristics, a higher S/N value corresponds to a better performance. Therefore, the optimal level of the system parameters is the level with the higher S/N value.

The S/N ratios computed from the experimental results are listed in Appendix II (Table - 35 – 38). The higher S/N ratio is desirable as it represents better output or drying characteristics (i.e more moisture removal/less moisture loss of the sample, higher diffusivity of the sample and higher efficiency of the dryer) with the different samples. It is observed that the higher temperature and air velocity causes removal of more water vapour from the samples leading to better drying operations. The increase of the temperature would increase the diffusivity during the moisture transport process.

An ANOVA Table breaks down the effect of each factor and calculates the experimental error. In addition, it also breaks down all of the possible interactions of the factors. In the present work ANOVA Table shown in Appendix II (Table - 39 – 42).

ANOVA analysis, which uses a simplified ANOVA method. ANOVA analysis is used to determine the contribution factor of each drying parameter in the drying process. Appendix II (Table - 39 – 42) presents the ANOVA analysis. Summary results of the ANOVA are shown in Appendix II (Table - 39 – 42) and indicate that all of the selected factors are significant parameters at the 95% confidence level ($p < 0.05$) on the drying process.

The P-value reports the significance level (suitable and unsuitable) in Appendix II (Table - 39 – 42). The value of P>F which is less than 0.0050 depict that the model is significant. Percent (%) is defined as the significance rate of the process parameters on the moisture loss of the samples. The percent numbers depict that the time, temperature and velocity have significant effects on the moisture loss. The coefficients of model for mean are shown in Appendix II (Table - 43 – 46).

It is observed that calculated values of different dryer outputs (i.e. moisture loss, diffusivity and efficiency) against the respective experimentally values show developments of correlations are proper.

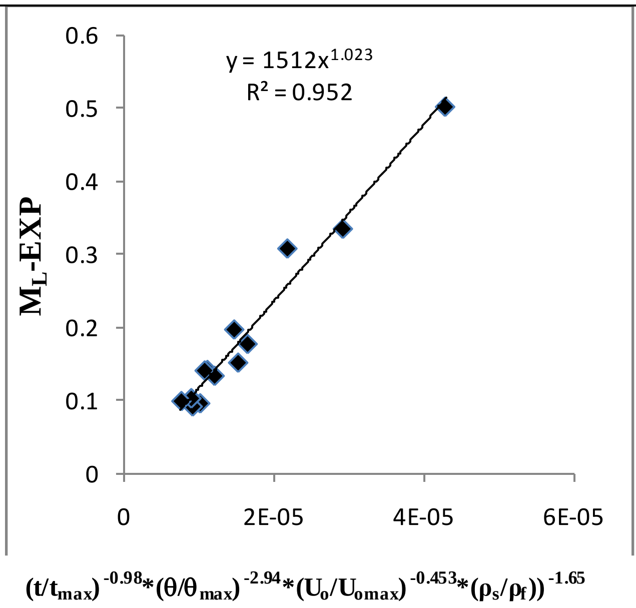


Fig. - 4.2: Correlation plot of moisture loss against the system parameters for grains

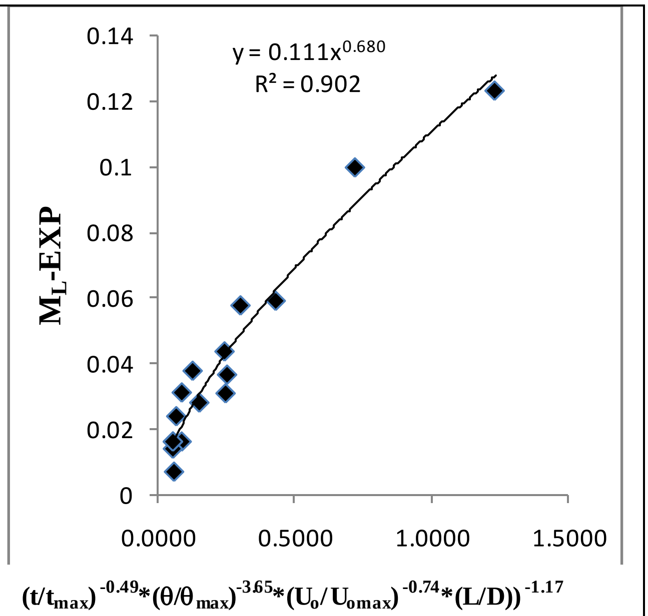


Fig. - 4.3: Correlation plot of moisture loss against the system parameters for vegetables

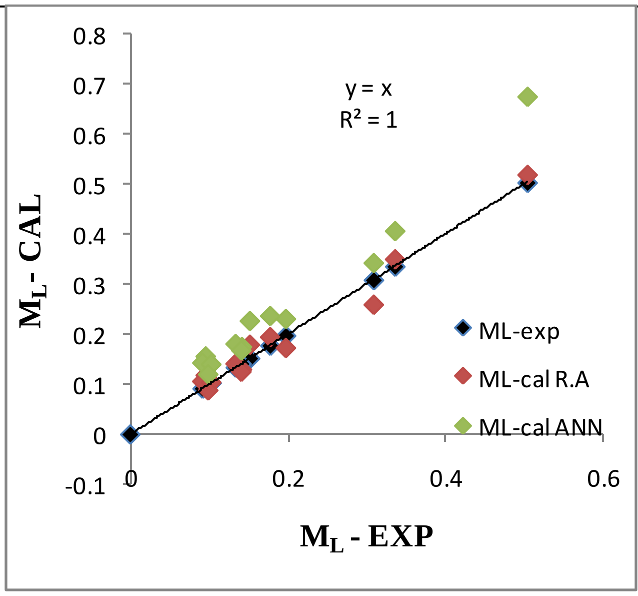


Fig. - 4.4: Experimental values vs. calculated values of moisture loss for grains

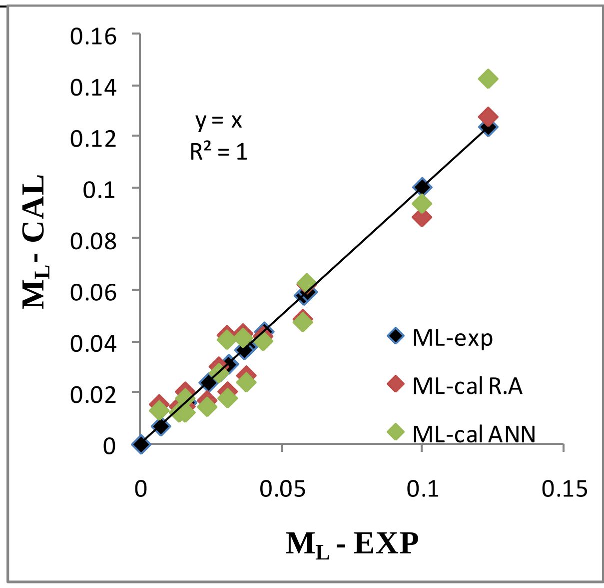


Fig. - 4.5: Experimental values vs. calculated values of moisture loss for vegetables

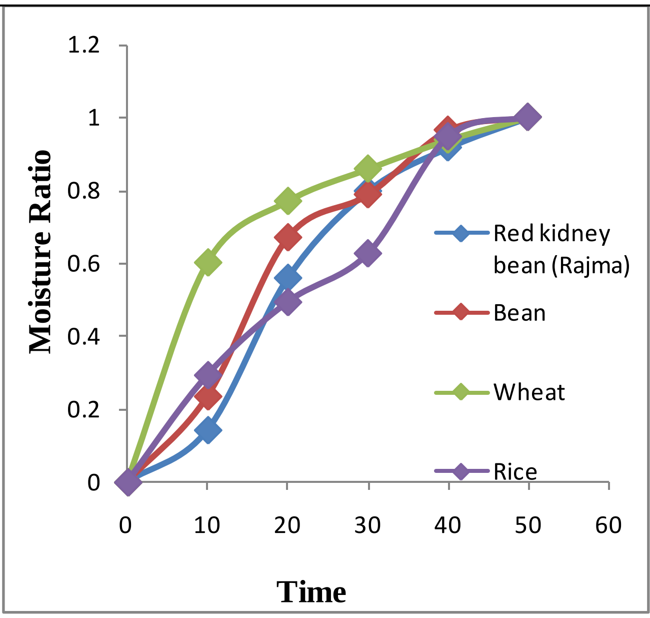


Fig. - 4.6: Variation of moisture ratio with time for grains

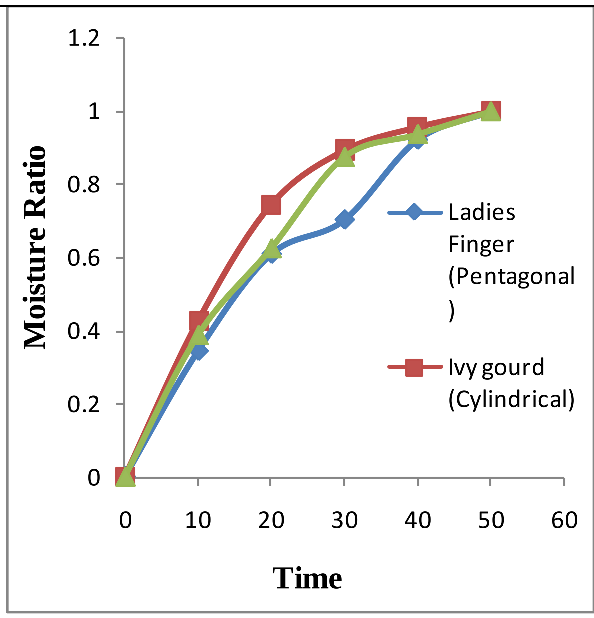


Fig. - 4.7: Variation of moisture ratio with time for vegetables

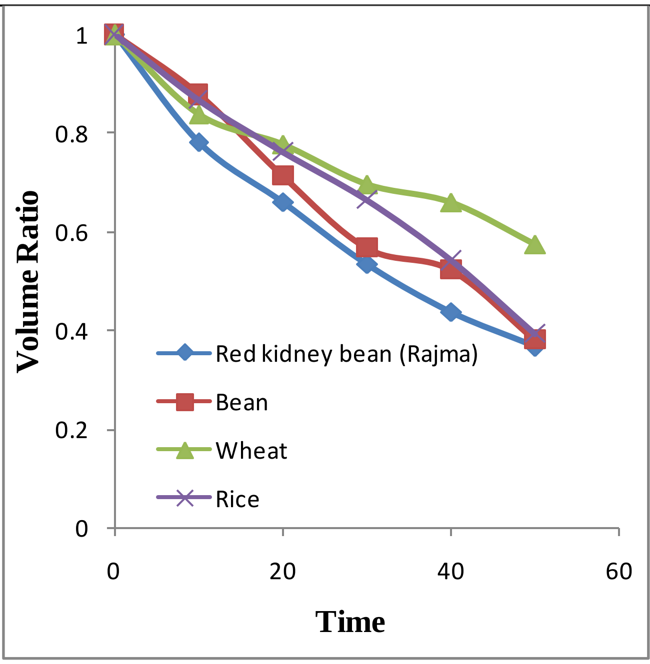


Fig. - 4.8: Variation of volume ratio with time for grains

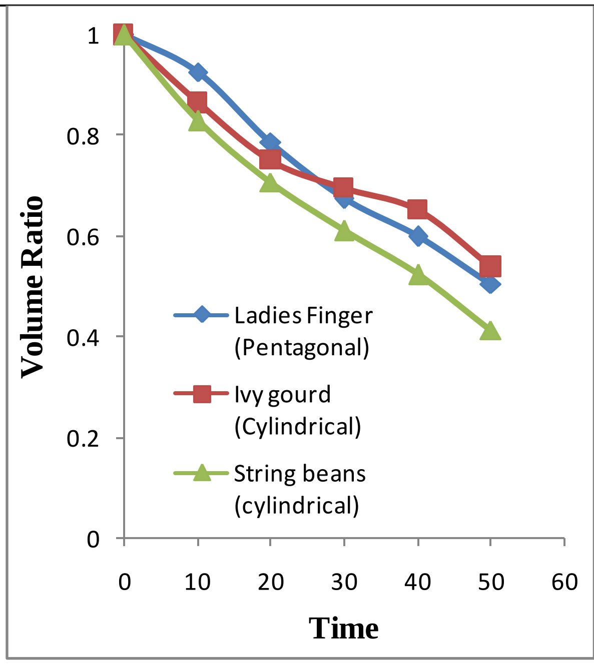


Fig. - 4.9: Variation of volume ratio with time for vegetables

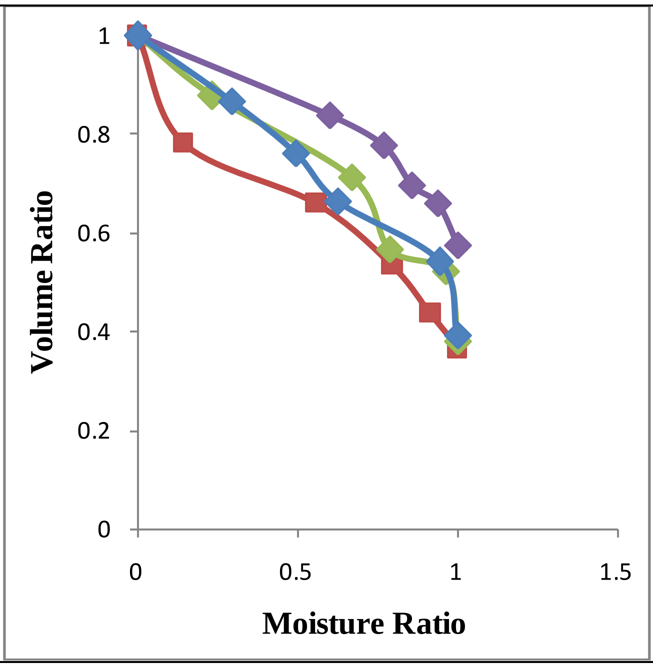


Fig. - 4.10: Variation of moisture ratio with volume ratio for grains

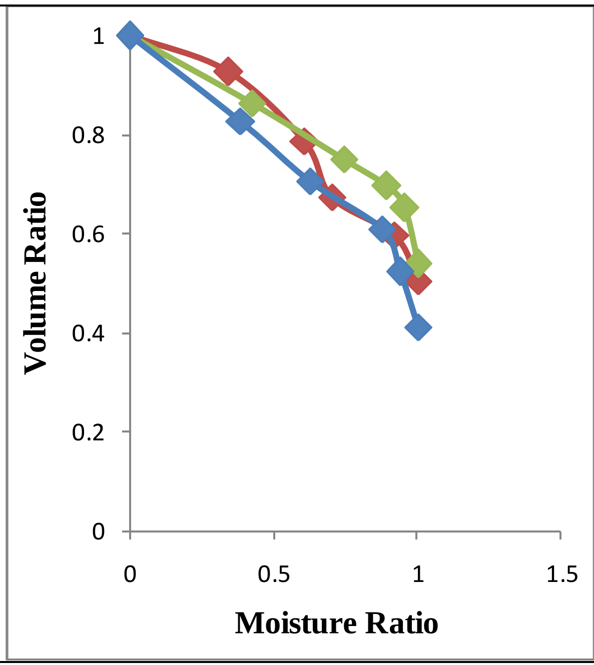


Fig. - 4.11: Variation of moisture ratio with volume ratio for vegetables

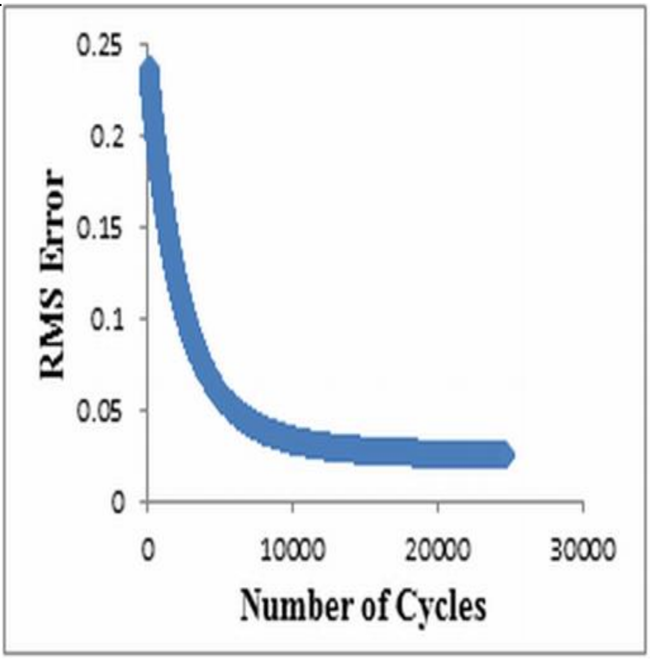


Fig. - 4.12: RMS error of ANN analysis against the number of cycles for grains

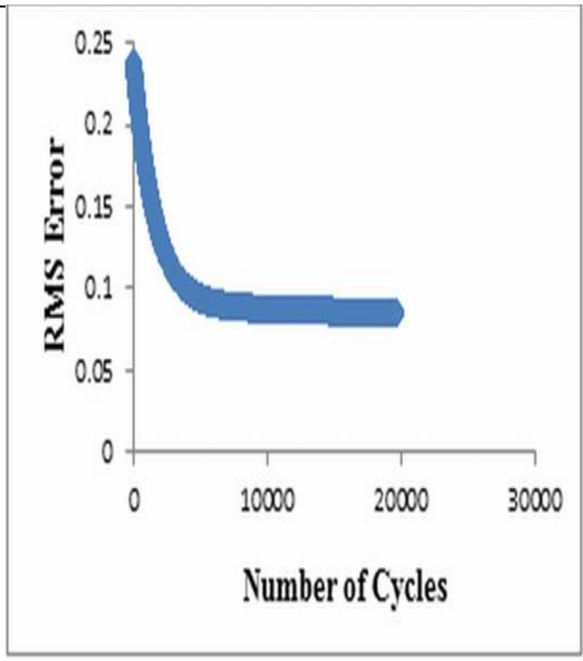


Fig. - 4.13: RMS error of ANN analysis against the number of cycles for vegetables

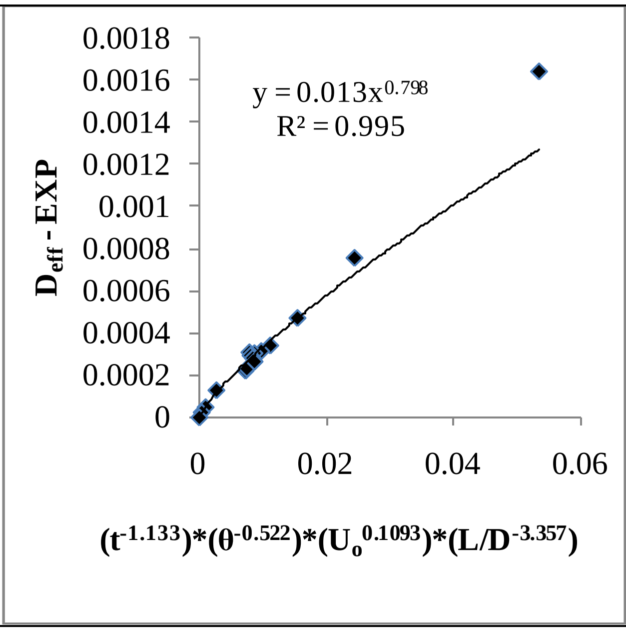


Fig. - 4.14: Correlation plot for the diffusivity of mushroom against the system parameters

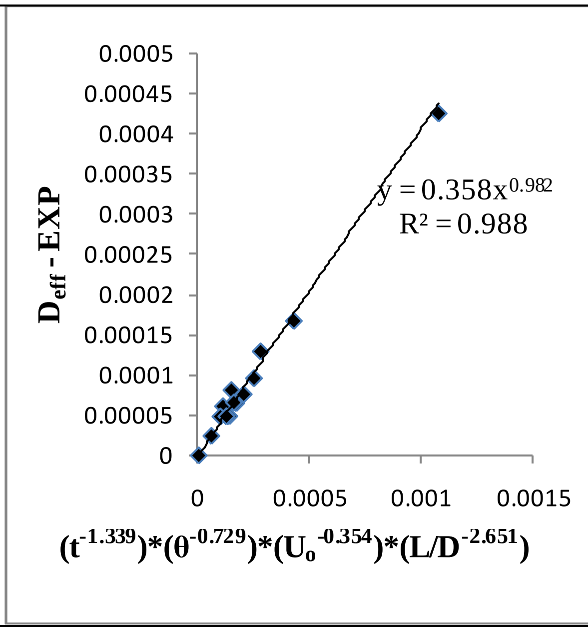


Fig. - 4.15: Correlation plot for the diffusivity of vegetables against the system parameters

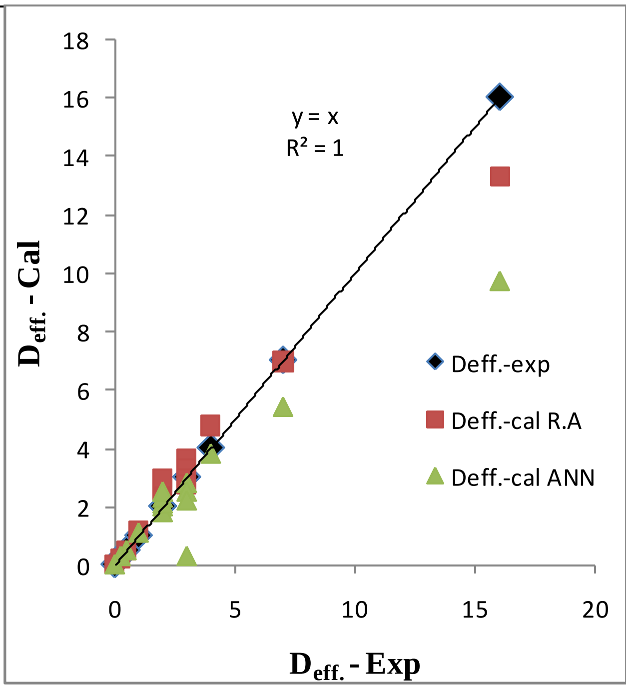


Fig. - 4.16: Experimental values vs. calculated values of diffusivity for vegetables

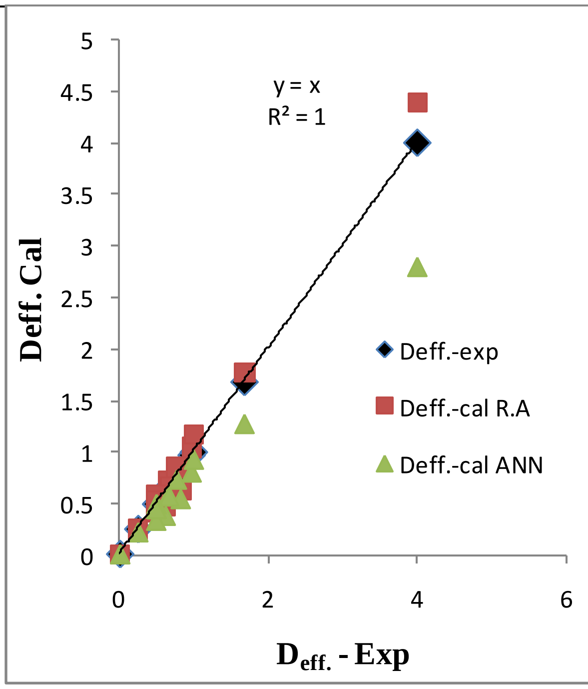


Fig. - 4.17: Experimental values vs. calculated values of diffusivity for mushroom

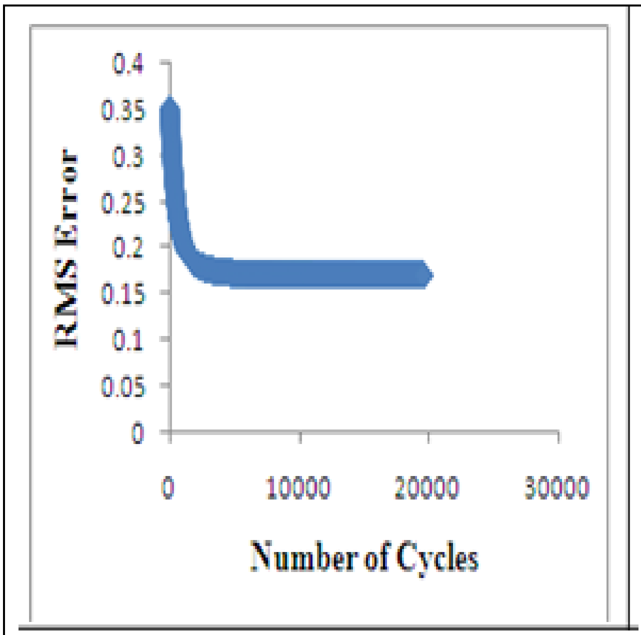


Fig. - 4.18: The RMS Error for mushroom against the number of epoches

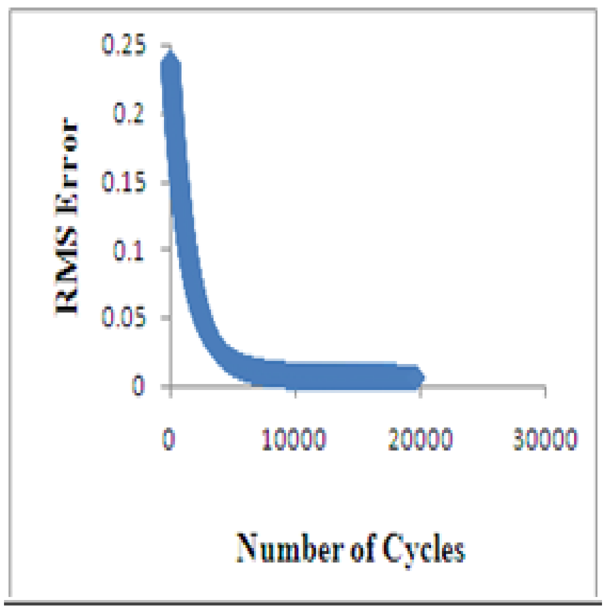


Fig. - 4.19: The RMS Error for vegetables against the number of epoches

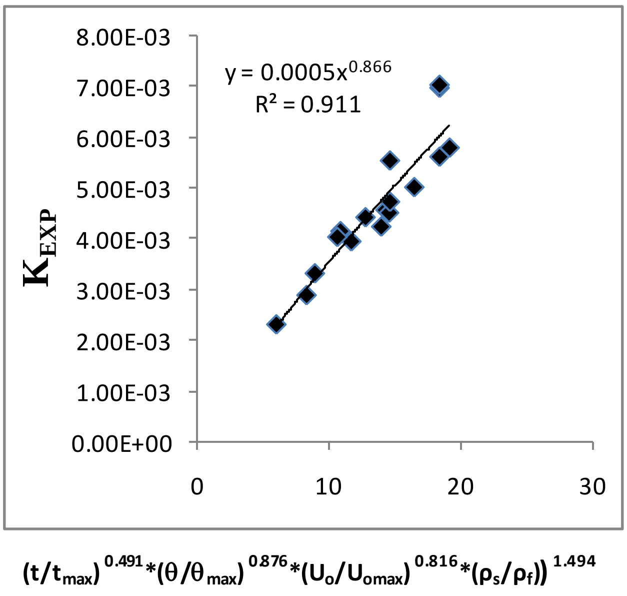


Fig. - 4.20: Correlation plot of mass transfer coefficient against the system parameters for grains.

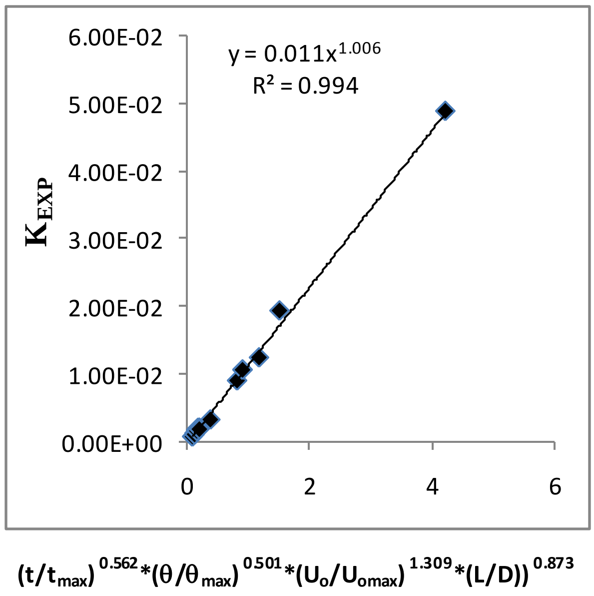
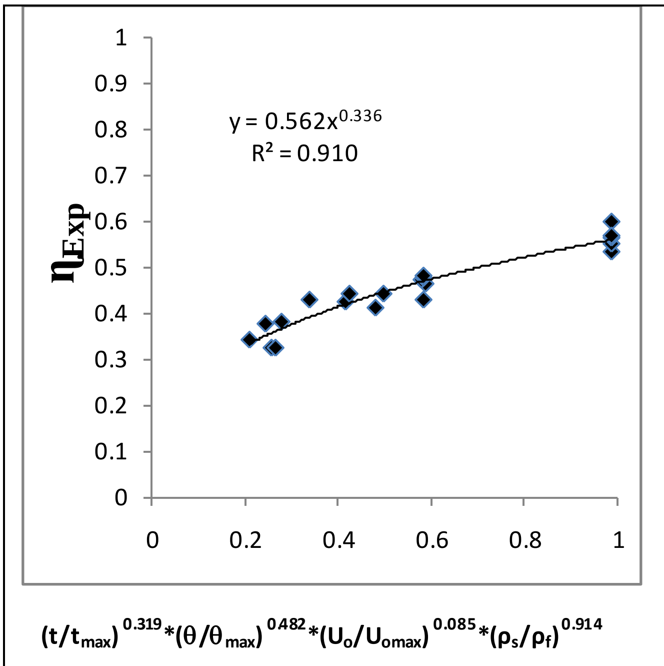


Fig. - 4.21: Correlation plot of mass transfer coefficient against the system parameters for vegetables.



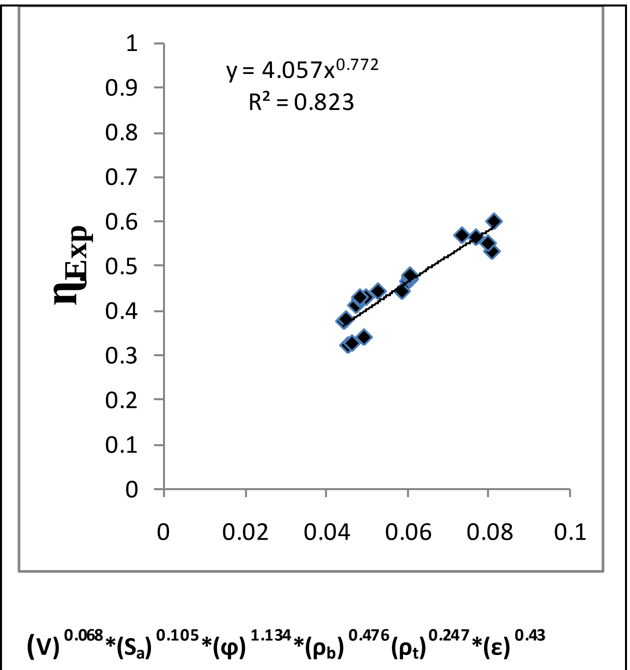


Fig. - 4.22: Correlation plot of efficiency against the system parameters for grains

Fig. - 4.23: Correlation plot of efficiency against the properties for grains

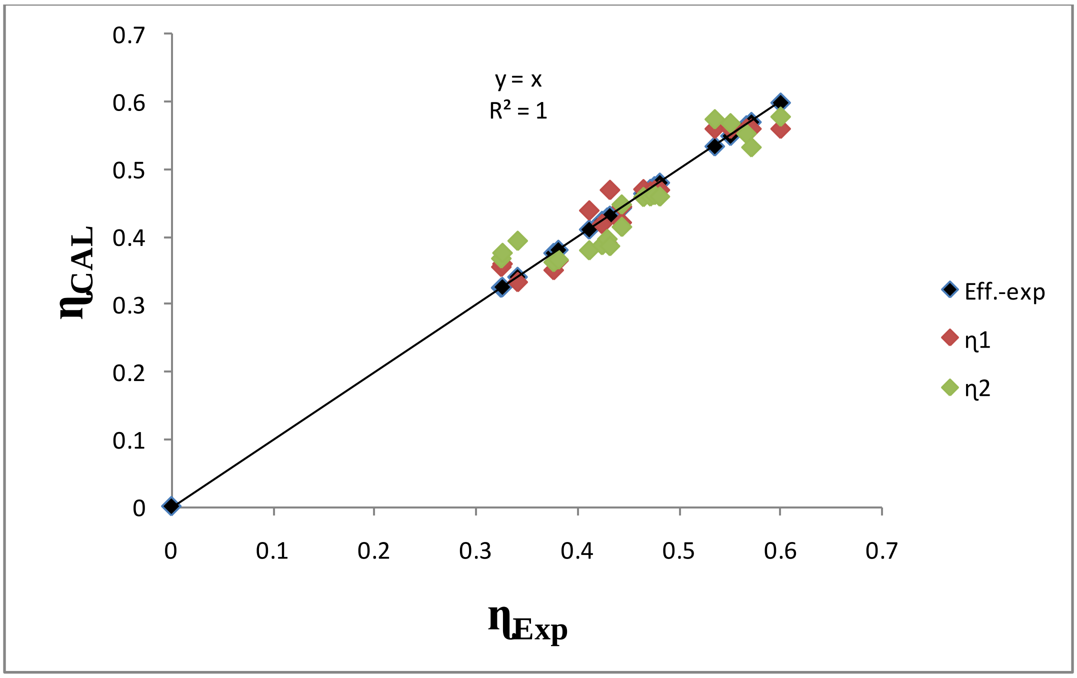


Fig. - 4.24: Comparison among experimental and calculated values of efficiencies for grains

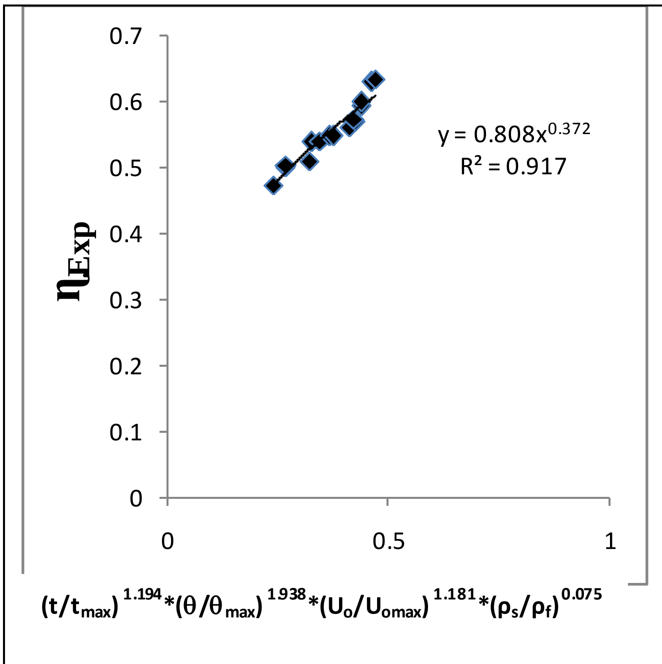


Fig. - 4.25: Correlation plot of efficiency against the system parameters for vegetables

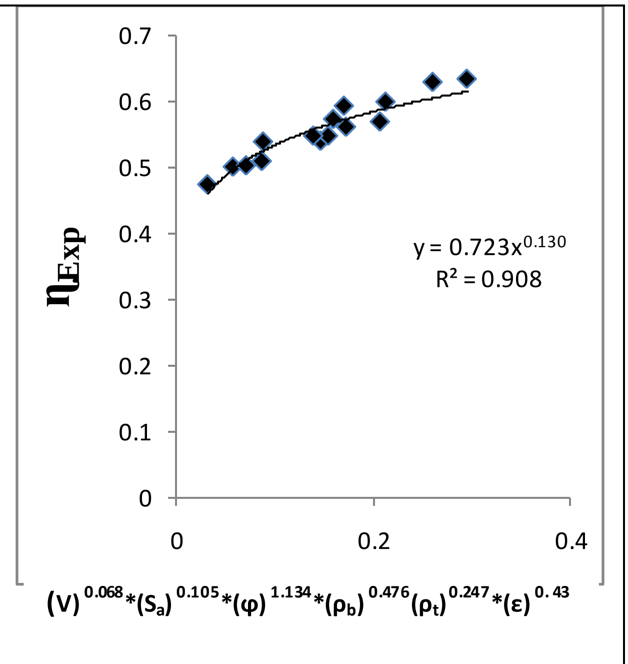


Fig. - 4.26: Correlation plot of efficiency against the properties for vegetables

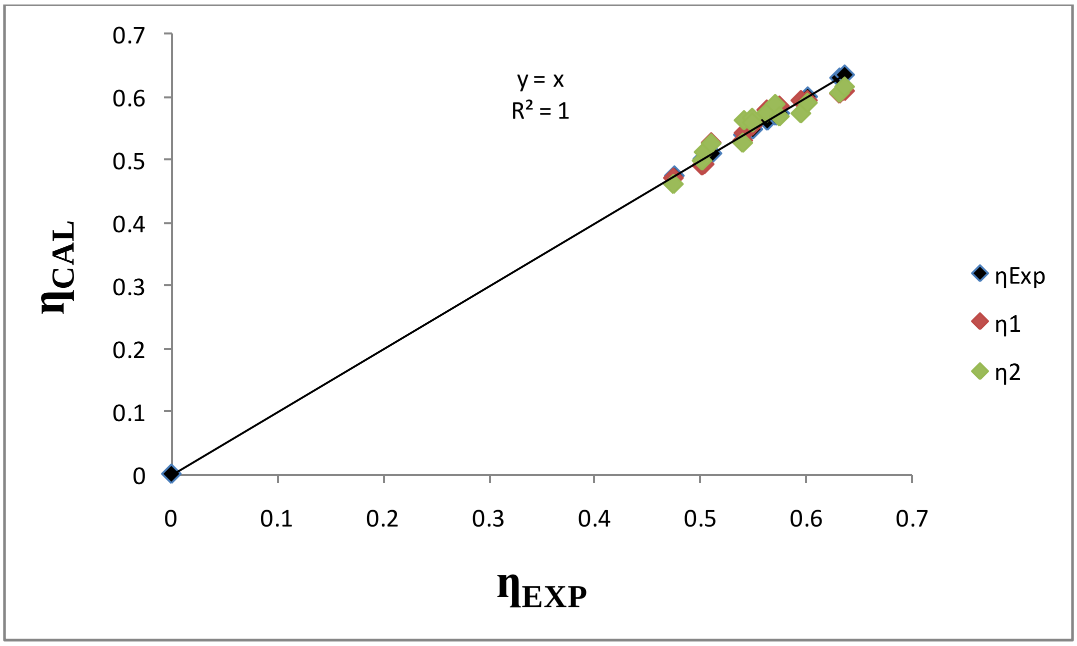


Fig. - 4.27: Comparison among experimental and calculated values of efficiencies for vegetables

CHAPTER V

DESIGN OF TAPERED FLUIDIZED BED DRYER

5.1. Introduction

Different agricultural products such as cereal, pulses, grains, oil seeds, etc. are not cultivated always. Demand for these agro products is enormous because of rapid growth in population at the global level. Survey shows that 25 and 40% of these agriculture products are spoiled every year without proper preservation technologies. Such crops which are harvested once in a year, needs to be stored properly to meet the demand round the year. Thus, there is a need to have an appropriate dryer design. An essential factor that is required for design and successful operation of the dryer is the selection of the optimum fluidization velocity which is best determined experimentally for the given material in a pilot plant. Any given sample of material has a minimum fluidization velocity. A satisfactory processing condition requires a velocity in excess of this. Published relationships for calculation of minimum fluidizing velocity are not reliable as they apply only to free-flowing substances of near spherical form and uniform size distribution. The majority of materials to be dried or cooled have a widerange of sizes and are irregular in shape. The fluidization velocity is significantly influenced by the cohesiveness of particles and varies very much with the moisture content and with temperature. Thus in practice, the material may need widely differing velocities as it passes through the different zones of a fluid bed.

During the constant rate period, rate of drying is controlled by the rate of heat and mass transfer between the particle surface and the drying medium i.e. external drying factors. In the falling rate period, conduction of heat and diffusion of moisture take place within the particle. These are rate controlling processes andtherefore the rate of drying is dependent of the internal drying factors, which cannot be influenced by fluidization.

Studies [99] however show that the traditional and some commercial dryers consume considerable time and energy in their operations and are very expensive. Therefore, it is required to develop a dryer that would lead to time reduction without compromising efficiency.In a tapered fluidizer cross sectional area increases gradually for which fluid velocity decreases with reduced velocity, contact time of hot fluid with bed materials increases as a result more moisture content is removed or more drying takes place.Therefore an attempt is made to design a tapered bed fluidized bed dryer.

Given the inability to predict the behaviourof the material under varying moisture conditions, removal of moisture from solids remains an art, and one has all the time resort to experiment.

5.2. Design calculation

Design of fluidized bed dryer includes calculation of volume (V), area of cross section (A_c) of the fluidizer along with energy and mass balances. Fluidized bed process conditions are also required to be determined with the above data. From the shape of the fluidizer it can be divided into two parts i.e. upper cylindrical part and lower circular cone frustum. It is as shown below (Fig.-5.1)

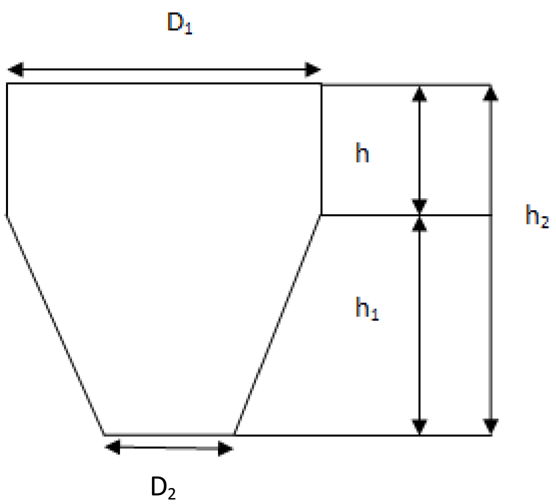


Fig. 5.1: Front view of the fluidizer

The volume (V) and cross sectional area (A_C) of the fluidizer can be calculated out as per the following.

5.2.1. Total Volume of Bed (V):

$$V = V_1 + V_2 \tag{5.1}$$

Where V_1 is volume of cylindrical part, V_2 is the volume for circular cone frustum part.

$$V = \frac{\pi}{4} D^2 h_1 + \frac{\pi h}{3}\left[R_1{}^2 + R_1 R_2 + R_2{}^2\right] \tag{5.2}$$

Thus, V can be calculated as

$$V = \frac{\pi}{4} * (21.96)^2 * 13 + \frac{\pi * 20}{3}\left[(6.05)^2 + 10.98 * 6.05 + (10.98)^2\right]$$

$= 4923.772 + 4682.898 = 9607 \text{ cm}^3$

The fluidization vessel is designed to have a volume of near about 9607cm^3 so as to have a maximum bed height of 15cm. The height of the circular cone frustum is 20 cm and the diameters are12.1cm at the lower end and 21.96cm at the upper end. The height of cylindrical portion is 13cm. This dryer does not occupy much space when fully installed and it is portable.

5.2.2 Area of Cross Section (A_C):

The cross sectional area of fluidizer can be calculated as the average of that of two sections i.e. average of cross sectional areas for cylindrical and circular cone frustum. Thus it can be written as

$$A_C = \frac{A_{C1} + A_{C2}}{2} \tag{5.3}$$

Where A_{C1} is the cross sectional area of cylindrical part and A_{C2} is the Cross sectional area of the circular cone frustum part.

Thus

$$A_{C1} = \frac{\pi}{4} D_1{}^2 = \frac{\pi}{4}(21.96)^2 = 378.752 cm^2 \tag{5.4}$$

The area of cross section circular of cone frustum can be expressed as a function of bed height and its calculation is carried out as follows.

$$A_{C2} = \int_0^h \frac{\pi r^2(z)}{h} dz \tag{5.5}$$

Where, $$r = R_1 + \frac{R_2 - R_1}{h} z \tag{5.6}$$

And 'z' is varying bed height

$$So, r^2 = R_1^{\ 2} + \left(\frac{R_2 - R_1}{h}\right)^2 z^2 + 2 * \frac{R_1 * (R_2 - R_1) z}{h} \tag{5.7}$$

$$\Rightarrow r^2 = R_1^{\ 2} + \frac{\left[R_2^{\ 2} + R_1^{\ 2} - 2R_1R_2\right] z^2}{h^2} + \frac{2R_1(R_2 - R_1)\ z}{h} \tag{5.8}$$

$$\Rightarrow r^2 = R_1^{\ 2} + \left(\frac{R_2 - R_1}{h}\right)^2 z^2 + 2 * \frac{R_1 * (R_2 - R_1) z}{h} \tag{5.9}$$

Further simplifying we get

$$r^2 = \frac{R_1^{\ 2} h^2 + \left(R_2^{\ 2} + R_1^{\ 2} - 2R_1R_2\right) z^2 + 2R_1 h (R_2 - R_1) z}{h^2} \tag{5.10}$$

Substituting the above expression for r^2 in Eq. - 5.3 and integrating area of cross section (A_{C2}) is calculated.

$$A_{C2} = \int_0^h \frac{\pi}{h^3} * \left[R_1^{\ 2} h^2 + \left(R_2^{\ 2} + R_1^{\ 2} - 2R_1R_2\right) z^2 + 2R_1 h (R_2 - R_1) z\right] dz \tag{5.11}$$

Now integrating above equation we get as follows.

$$A_{C2} = \frac{\pi}{h^3} * \left[R_1^{\ 2} h^2 z + \left(R_2^{\ 2} + R_1^{\ 2} - 2R_1R_2\right) \frac{z^3}{3} + h\left(2R_1R_2 - 2R_1^{\ 2}\right) \frac{z^2}{2}\right]_0^h \tag{5.12}$$

$$\Rightarrow A_{C2} = \frac{\pi}{h^3} * \left[R_1^{\ 2} h^2 z + \left(R_2^{\ 2} + R_1^{\ 2} - 2R_1R_2\right) \frac{z^3}{3} + \left(R_1R_2 - R_1^{\ 2}\right) h z^2\right]_0^h \tag{5.13}$$

Where, z_{max} = h, zmin = 0

But in a fluidizer, z_{max} can not be equal to h. For proper fluidization 'z' should be much less than 'h' that is why 'z' can be taken as H_b(bed height).

Considering bed height of 15cm, we have the fluidizer dimensions as follows.

h = 20 cm, z_{max} = 15 cm (considering), R_1 = 6.05 cm, R_2 = 10.98 cm

Substituting these values in Eq. -5.12 we get the cross sectional area as

$$A_{C2} = \frac{\pi}{(20)^3} * \left[(6.05)^2 * (20) * 15 + \left[(10.98)^2 + (6.05)^2 - 2*6.05*10.98 \right] \frac{(15)^3}{3} + 20*\left(2*6.05*10.98 - 2*(6.05)^2\right) * \frac{(15)^2}{2} \right]$$

$$= 149.688 \text{ cm}^2 \approx 150 \text{ cm}^2$$

Considering Wheat as bed material with static bed height less than 10 cm for a case study, expanded bed height can reach around 15 cm. Thus average area of cross section can be calculated as

$$A_C = \frac{378.752 + 149.688}{2} = 264.22 cm^2 \approx 264 cm^2$$

5.2.3. Bed pressure drop:

(Drag force by upward moving gas) = (weight of particles)

Or,

(Pressuredrop acrossbed)(Crosssectionalarea of tube) = (Volume of bed)(Fracion cosisting of solids)(Specific weight of solids)

Thus, bed pressure drop can be calculated as

$$\Delta P * A_t = V_b * (1-\varepsilon) * (\rho_S - \rho_g) * g \tag{5.14}$$

Considering air as fluidizing medium where, ρ_g =0.00107gm/cc, ε = 0.2 and substituting the values we get

$$\Delta P * \left(\frac{\pi}{4} * (12.1)^2 \right) = \frac{\pi}{3} * 15\left((6.05)^2 * (6.05*9.8) * (9.8)^2 \right) * (1.351 - 0.00107) * 9.81 * (1-0.2) = 2778 \text{ N/m}^2$$

5.2.4. ε_{mf} for the fluidized bed dryer:

The ε_{mf} for the bed is needed in determining the minimum fluidization velocity for the bed. This ε_{mf} is the void fraction at the point of the minimum fluidization. It appears in many of the equations describing the fluid-bed characteristics and is computed as follows.

Hence

Voidage at minimum fluidization can be written as

$$\varepsilon_{mf} = \left|\left((0.586)*(\psi)^{-0.72}\right)\left(\frac{\mu^2}{\rho_g \eta d_p{}^3}\right)^{0.029} * \left(\frac{\rho_g}{\rho_s}\right)^{0.021}\right. \tag{5.15}$$

And

$$\eta = g(\rho_S - \rho_g)$$

= 9.81*(1.351 - 0.00107)

= 13.2 = 1324.28 gm/cm^2 sec^2

$$= \left(0.586*(0.7)^{-0.72}\right)\left[\frac{(1.5*10^{-4})^2}{0.00107*1324.3*(0.005)^3}\right]^{0.029}\left(7.885*10^{-4}\right)^{0.021}$$

= 0.478 ≈ 0.5

5.2.5. Reynolds number (Re):

This is a dimensionless parameter that affects the characteristics of the two velocities involved in the study i.e. the minimum and the maximum fluidization velocity.

$$\mathrm{Re} = \frac{\rho_p d_p V_p}{\mu} \tag{5.16}$$

$where, V_p = \frac{\pi d_p{}^3}{6}$ = volume of particle

ρ_p = density of particle = 1100 kg/m^3 (For wheat in the present case)

μ = viscosity = 1.5*10^{-5} kg/m s

d_p = particle diameter = 5mm = 0.005 m

Thus substituting these values in Eq. - 5.16 we get Reynolds number as follows.

$$\mathrm{Re} = \frac{\left(\frac{1100*0.005*\pi(0.005)^3}{6}\right)}{1.5*10^{-5}}$$

= 0.0239 = 23.9*10^{-3}

Since the Re is less than 10, it gives the type of flow in the fluidizing vessel as a laminar flow and maximum fluidizing velocity needed for the system. Thus it can be said that the flow is laminar.

5.2.6. Minimum fluidization velocity (u_{mf}):

This is the minimum velocity needed to blow the particles of the bed. It is the velocity required to begin the fluidization at which the weight of particles, gravitational force equals the drag on the particles from the rising gas.

$$U_{mf} = \left[\frac{(\psi d_p)^2}{150\mu} \eta * \left[\frac{(\varepsilon_{mf})^3}{(1-\varepsilon_{mf})} \right] \right] \tag{5.17}$$

Where, $\eta = g(\rho_c - \rho_g) = 13.2$

and

Φ = Sphericity = 0.7

Thus substituting these values in above Eq. - 5.17 we get

$$U_{mf} = \left[\frac{(0.7 * 0.005)^2}{150 * 1.5 * 10^{-5}} (13.2) * \left[\frac{(0.478)^3}{(1-0.478)} \right] \right]$$

= 0.0150 m/s = 1.5 cm/sec

5.2.7. Maximum fluidization velocity:

The maximum velocity needed for the particles inside the bed. The maximum fluidization velocity is calculated for the bed so as to avoid chaotic situation where the particles will not be blown out of the bed. The drag on the particles will surpass the gravitational force on the particle and the particles will been trained in the gas.

Since Reynolds Number is less than 10, the following equation can be used for calculation of terminal velocity.

$$U_t = \frac{\eta d_p^{\ 2}}{18\mu} \tag{5.18}$$

$$= \frac{13.2 * (0.005)^2}{18 * 1.5 * 10^{-4}}$$

= 1.2222 m/s = 122.22 cm/sec

5.2.8. Inlet pipe:

The feed inlet pipe was designed to supply air. The expression used in the calculation of the pipe flow rate into the bed is based on

$$f_r = \text{inlet pipe flow} = \frac{1}{4}\pi P_i^{\,2} u \tag{5.19}$$

Where u is the velocity of air at the pipe out let which is also same as superficial fluid velocity for the fluidization process. Considering u = 0.97 m/s = 97 cm/s

$$or,\ f_r = \frac{\pi * (5.57)^2 * 97}{4} = 2362.39\, cm^3/\sec$$

5.2.9. Mean residence time for hot air:

This is the mean time during [which the molecules of hot air remain on the surface of the bed .i.e. the mean time interval between impact and drying.

$$\tau = \frac{V}{f_r} = \frac{9607}{2362.39} = 4.06\, s \tag{5.20}$$

5.2.10 Pressure drop in the fluidized bed dryer

ΔP, the pressure drop across the bed is closely related to drag force and is calculated based on

$$\Delta P_g = h A_C \Delta T \tag{5.21}$$

Maximum temperature limit is 110^{o}C. Sample set temperature of hot air may be taken as 70^{o}C

T_{max} =110^{o}C, t_1 = 20^{o}C, t_2 = 40 ^{o}C (considering that material is heated up to 40^{o}C)

= h*264.22*(40-20) = 5284 h N/m^2

If h value is known pressure drop can be calculated.

5.3. Single – phase model

Many mathematical models of fluidized bed drying have been proposed in literature and verified with experimental data. Single phase model is one of these models where the entire bed is considered to be in a single phase.

In a single-phase model, the fluidized bed is regarded essentially as a continuum (Fig. - 5.2). Heat and mass balances are applied over the fluidized bed. It is assumed that particles in the bed are perfectly mixed. Eq. - 5.22 & Eq. - 5.23 represents the material balance and energy balance, respectively [100].

5.3.1. Material Balance:

$$M_s \frac{\overline{dX}}{dt} = Gg(Y_{out} - Y_{in}) \tag{5.22}$$

Where M_s is the mass hold-up of dry solid in bed (kg), X is the average moisture content (kg/kg), G_g is the mass flow rate of dry air (kg/s), and Y is the air humidity (kg of water vapor) / (kg of dry air).

5.3.2. Energy Balance:

In general energy balance equation can be written as

$$\text{Heat supplied by drying medium} = \text{Heat consumed for heating material} + \text{Heat consumed for evaporating the moisture}$$

Or, mathematically it can be expressed as

$$M_s C_{ps} = G_g\left(C_g + Y_{in} C_v\right)\left(T_{in} - T_{out}\right)dt - G_g\left(Y_{out} - Y_{in}\right)\lambda \tag{5.23}$$

Where c_p is the heat capacity at constant pressure (kJ/ kg K) and λ is the latent heat of vaporization (kJ/kg). Subscript ‘‘s’’ denotes wet solid, ‘‘g’’ denotes dry air, and ‘‘v’’ denotes water vapor. Eq. - 5.23 neglects sensible heat of the water in solids.

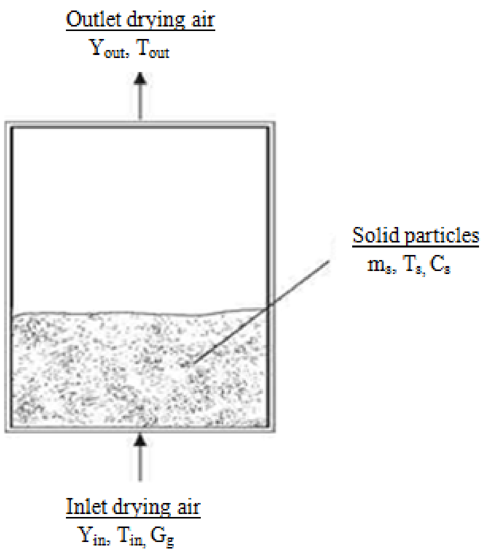


Fig. - 5.2: Schematic diagram of the fluidized dryer with single-phase model [100]

5.4. Design Procedure

Design procedures for batch dryer's inconstant and falling rate periods are studied. The discussion here is restricted to particulate solids drying.

5.4.1. Residence Time:

In the present work, soaked materials are used for drying experiments using a batch dryer. From the drying curves of all the samples it is observed that drying mostly occurs in the falling period. Initially very short period of constant drying is observed. Reason may be due to fact that if the solid particles initially contain surface moisture, falling rate period will occur after a short period of constant rate period [100]. Thus total residence time can be divided in two parts i.e. one part for constant rate period and other part for falling rate period. Mathematically it can be written as

$$t_{R1} = t_{R1} + t_{R2} \tag{5.24}$$

Where, t_{r1} is residence time for constant rate period, t_{r2} is residence time for falling rate period.

A tapered fluidized bed can be designed with respect to one feed sample.

Let us consider 300 gm Wheat as feed material (at this makes the bed height at 10cm in the fluidizer) and feeding time of 225 sec. The observed data are summarised as follows.

Thus $Fs = \frac{300}{225} = 1.33 * 10^{-3}$ kg/s

Initial moisture content X_{in} = 46%

Final moisture content after drying X_{out} = 17%

Inlet temperature of hot air = 70°C

Particle temperature or temperature dry sample = 40°C

Initial particle temperature = 20°C

Inlet humidity of air = 0.005 kg H_2O/kg of dry air

Thus the dryer design calculations can be carried out as follows.

$$t_R = t_{r1} + t_{r2} = \frac{(X_O - X) M_S \lambda}{G_g C_{pg} (Ti_n - T_{out})} + \frac{M_S C_{ps}}{G_g C_{pg}} \ln \frac{(T_p - T_{in})}{(T_{po} - T_{in})} \tag{5.25}$$

$$t_R = \frac{(0.46 - 0.17) 0.34 * 2270}{0.4787 * 1.05 * (70 - 40)} + \frac{0.3 * 1.5}{0.4787 * 1.05} \ln \frac{(40 - 70)}{(20 - 70)} = 126.41 \sec$$

5.4.2. Sizing of Bed:

Sizing of bed is based on simple hold-up mass balance. Cross-sectional area of the fluidized bed can be determined from the following equations.

Where solids flow rate (dry basis), Fs, bed density, ρ_b, and bed height, H_b and particle residence time, t_R, are determined.

5.4.3. Bed density:

During fluidization of solids at a bed height of 10cm, H_B can be maximum of 20cm. So with $(H_B)_{max}$=20cm i.e. bed height of tapered portion only. Thus volume of circular cone frustum (V_2 = 4670cm^3) is considered for calculation of bed density.

$$\rho_b = \frac{\text{Mass of bed during fluidizati on}}{\text{Volume of bed during fluidizati on}}$$

$$= \frac{0.3}{4670 * 10^{-6}} = 64.24\text{Kg/m3}$$

Thus area of bed can be calculated as:

$$A = \frac{F_s t_r}{\rho_b H_B} \tag{5.26}$$

$$A = \frac{1.33 * 10^{-3} * 126.4}{64.24. * 0.1} = 0.0262 = 262\,cm^2$$

This value is almost same as calculated area of cross section. (Since average area of cross section of the fluidizer 264.5cm^2).

5.4.4. Gas Flow Rate:

Gas flow rate (dry basis) is calculated from the following equation. The operating gas velocity, U_g, is specified as a multiple of the minimum fluidization velocity. The suitable operating gas velocity can thus be determined from laboratory-scale fluidized bed testing as long as the gas velocity yields good fluidization quality during the operation.

$$G_g = U_g \rho_g A \tag{5.27}$$

Where, A is the cross section of fluidizer at the bottom end where air enters the bed. It as follows

$$A = \pi R_2{}^2 = \pi * 6.05\text{cm2}$$

$$= 114.99\text{cm}^2 = 0.011499\text{m}^2 = 0.115\text{m}^2$$

Thus G_g can be calculated as

$$G_g = 3.89 * 1.07 * 0.0115 = 0.04787\text{m}^3/\text{s}$$

5.5. Mass balance

$$F_s(X_{in} - X_{out}) = G_g(Y_{out} - Y_{in}) \tag{5.28}$$

In this equation, F_s is the solids flow rate (kg/s), X is the moisture content (kg/kg), G_g is the gas flow rate (kg/s), and Y is the absolute humidity (kg/kg).

$$= 1.33 * 10 - 3 * (0.64 - 0.17) = 0.04787 \ (Y_{out} - 0.005)$$

$$Y_{out} = 0.01305 = 0.013 \ \frac{\text{kg of } H_2O}{\text{kg of dry air}}$$

5.6. Energy balance

Heat balance for the single-phase model gives the following energy balance:

$$F_S H_{Sin} + G_g H_{gin} + Q_h = F_S H_{Sout} + G_g H_{gout} + Q_L \tag{5.29}$$

In this equation, Q_h is the rate of heat input from immersed tubes (kj/s), Q_L is the rate of heat loss from wall (kj/s), and H is the enthalpy (kj/kg). Enthalpy of solids at the inlet and outlet can be obtained from equation respectively:

$$H_{sin} = (C_{ps} + X_{in} C_l) T_{sin} \tag{5.30}$$

$$= (1.05 + 0.46 * 4.2) * 20 = 59.64 \text{kg/kg}$$

$$H_{sout} = (C_{ps} + X_{out} C_l) T_{sout} \tag{5.31}$$

$$= (1.5 + 0.17 * 4.2) = 2.214 T_{sout} \ \text{kj/kg}$$

$$H_{gin} = (C_{pg} + Y_{in} C_l) T_{gin} + Y_{in} \lambda \tag{5.32}$$

$$= (1.05 + 0.005 * 4.2) * 70 + 0.005 * 2270 = 86.32 \text{kj/kg}$$

$$H_{gout} = (C_{pg} + Y_{out} C_l) T_{gout} + Y_{out} \lambda \tag{5.33}$$

$$= (1.05 + 0.013 * 4.2) T + 0.013 * 2270$$

$$= 1.1046T + 29.51$$

$$F_s H_{sin} + G_g H_{gin} + Q_h = F_s H_{sout} + Gg H_{gout} + Q_h \tag{5.34}$$

$$= 1.33 * 10^{-3} * 59.64 + 0.04787 * 86.32 = 1.33 * 10^{-3} * 2.214T + 0.04787 * (1.1046T + 29.51) + 0.005 * 0.04787 * (1.1046T + 29.51)$$

$$T = 46.663^{o}C$$

From the psychometric chart, air at absolute humidity of 0.013 kg/kg has a dew point of 26^oC and relative humidity is 20%. Since the outlet air leaves the dryer at 44.66^oC (20^oC higher than the dew point), there is no risk of condensation.

5.7. Performance Tests

Tests were carried out on the designed fluidized bed dryer to ascertain its performance. The analysis is carried out to determine the moisture reduction of different grains and vegetables during the drying process.

Sample calculations were carried out using the following formula.

Moisture content in sample (M_C) = original weight (W_b) less final weight (W_d).

$$\text{i.e. } M_C = W_b - W_d \tag{5.35}$$

$$\%M_C = \frac{\text{Weight loss}}{\text{Weight gain of the original sample}} X100$$

$$M_C = \frac{M_C}{W_b} X100 \tag{5.36}$$

5.7.1. Efficiency of the system (E_{ff}):

$$1 - M_C = E_{ff} \tag{5.37}$$

The results of the tests on the designed fluidized bed dryer were taken at 10 minutes interval to ascertain its efficiency. The values of percentage of moisture reduction and efficiency of the designed equipment are shown in Table - 5.1, 5.2, 5.3, & 5.4.

Table - 5.1 Percentage of Moisture reduction in grains samples

% Moisture Content Reduced				
Time	Red kidney bean	Bean	Wheat	Rice
10	5.71	13.5	5.5	5.71
20	7.86	17.05	8	7.86
30	12.06	22.32	9.6	12.06
40	14	27	10.64	14
50	17.25	30.17	19.2	17.25

Table - 5.2 Percentage of Moisture reduction in vegetables samples

% Moisture Content Reduced			
Time	Ladies finger	Ivy gourd	String Beans
10	5	8	10.87
20	7.24	9	12.23
30	9.57	10.89	14.87
40	12.5	12.23	15
50	14	13.5	19.05

Table - 5.3 Efficiency of the fluidized bed dryer for grains

Efficiency				
Time	Red kidney bean	Bean Seed	Wheat	Rice
10	0.94	0.87	0.95	0.91
20	0.92	0.83	0.92	0.90
30	0.88	0.78	0.90	0.88
40	0.86	0.73	0.89	0.87
50	0.83	0.70	0.81	0.86

Table - 5.4 Efficiency of the fluidized bed dryer for vegetables

Efficiency			
Time	Ladies finger	Ivy gourd	String Beans
10	0.95	0.92	0.89
20	0.93	0.91	0.88
30	0.90	0.89	0.85
40	0.875	0.88	0.85
50	0.86	0.87	0.81

5.7.2. Power consumption:

Power consumption for the drying experiments was calculated to be 0.87hp. Calculation details are given below.

Rating of energy meter is 1200 revolutions = 1 kwh

Thus 1 revolutions = 1/1200 kwh

While running the dryer it was observed that 1 revolution is completed in 2.47min and energy consumption is 1/1200 kwh.

Or, it can be said that in 2.47 min 1 revolution is completed.

In 10 mins time, the revolutions completed will be = $\frac{10}{2.47} revolutions = 3.374 * 10^{-3} kwh$

It is further observed that the energy meter reading during drying 250 gms of the wet samples for 10 mins time is 0.14kwh. This value indicates the total energy required for drying the sample and running the dryer.

Thus energy required for drying the sample only is the difference of the above two values.

So energy required for drying $= 0.14 - 3.374 * 10^{-3} kwh = 0.136626 kwh$

So power consumption will be =

$$\frac{\text{Energy meter reading}}{\text{Time}} = \frac{0.136626}{\left(\frac{10}{60}\right)} = 0.819756\ kw = 1.099\, hp \approx 1.1 hp$$

Mass balances, energy balance, residence time of solids are also calculated. The calculated values obtained through the design calculations confirm that no condensation takes place. Thus it can be said that dryer design is proper. Performance tests were also carried out on the designed machine by comparing. Moisture reduction and efficiency of different samples are evaluated during drying process. The comparison results indicate the higher efficiency for Wheat sample (from grains) and Ladies finger sample (from vegetables) [Table- 5.3 and 5.4]. Efficiency calculation shows that drying efficiency for a grain varies within 86 to 91 percent where as drying efficiency for the vegetables varies within 81 to 89 percent. Thus it can be said that the design dryer is better suitable for drying grains because of comparatively regular shapes.

The results of the tests on the dryer further implies that time interval of 10 mins to ascertain the efficiency is not much in comparison with power consumption for medium type flow of 2-5 hp/1000 gal [101]. The power consumption for the present dryer (1.1hp) conforms the design to be economical.

CHAPTER VI

CONCLUSIONS

6.1. Chapter wise conclusion

In the present work, the drying performances of fluidized bed dryer have been analyzed experimentally by varying four different system parameters viz. temperature, time of drying, velocity of air and density of bed material. The drying characteristics of various samples such as grains and vegetables are also studied through the moisture content of the samples estimated under different conditions. This study reveals that removal of moisture is more with the sample whose initial moisture content is more.

It is observed that there is a relation between volume reduction and drying constant during drying which in turn depends on the shape or size and structure of the material. Thus, information on shape and structure of feed sample can be useful to know the requirement for intensity of drying beforehand which will minimize the energy requirement to a much extent.

Validation of the developed correlations on moisture content against the experimentally observed data reveals that these correlations can be used over a wide range of parameters.

Mainly the temperature parameter is found to control the drying rate significantly by which the drying time is also controlled. As the drying time is a function of the moisture content of sample, increase in temperature of drying air decreases the drying time. The drying process is observed to occur in both falling rate and constant rate periods.

Based on the results of the error analysis for ANN-approach it is found that the neural network with the selected neurons, transfer function and with the back propagation algorithm are appropriate to selected ANN configuration.The very good agreement between ANN-model and experimental data proves that training of the neural network is proper. Thus it can be said that the selected ANN model successfully learned the relationship between the input parameters and output parameters.

Therefore, the suggested neural network can easily be used to normalize any experimental data of the drying process under different conditions.

Finally, it can also be said that the developed correlation can suitably be scaled up for the industrial dryer design or drying operation with a scale-up factor. The developed correlation can also be considered as the basis of the design for an industrial fluidized bed dryer (large scale) with the optimum drying conditions.

After analyzing moisture content of the samples, the diffusivity of the samples is studied during the drying operation. Attempts are made to develop correlations for these diffusivities of the samples on the basis of Regression analysis that are further validated by Artificial Neural Network approach. Comparing the calculated values of the diffusivities with the experimental values, excellent agreement is achieved indicating the validity of the correlation to be very good. Therefore, the developed correlations can be used over a wide range of parameters to measure the diffusivity of different samples. Heat transfer, mass transfer along with their kinetics is also analyzed during drying of different samples in the present study.

The drying characteristics of different samples such as mushrooms and vegetables are studied through the diffusivity of the samples. Drying kinetics for mushroom and vegetables are also observed through the measurement of activation energy and mass transfer coefficients. Knowledge of activation energy is a great help for optimization of the drying operation thereby minimizing the wastage of energy. The coefficients of the developed models and the apparent diffusion coefficients are the most important parameters for the transferring of moisture. These are also found to be dependent on the temperature and velocity of the drying air.

Mass transfer coefficient in a fluidized bed dryer is determined experimentally. Comparisons among the measured and calculated values of mass transfer coefficients show reasonable agreement. The experimental findings with the varied mass transfer coefficients, K confirm the influences of several parameters

The drying of samples in a fluidized bed dryer mainly takes place as a result of moisture transfer from the dense solid phase. In this study, the mass transfer coefficient is estimated from experimental measurements performed at different drying conditions. The results are used for validation of the values obtained from the developed empirical correlations. Despite the complexity of the process and the number of assumption employed in this analysis, diffusion mass transfer seems to provide satisfactory agreement with the experimental measurements.

Physical properties of samples are determined at different levels of moisture contents. Effects of moisture content on different properties viz. grain volume, surface area, sphericity, bulk density,actual density, porosity, etc. are studied. The effects of various system parameters (viz. time, temperature, velocity and density/shape of material) on moisture content are also considered. Thus, it can be concluded that different system parameters have effects on the physical properties of the samples. Therefore, knowledge of physical properties of the sample can give information on optimum conditions for the dryer. Thus, the developed correlations can be used for the proper design of a fluidized bed dryer by which a cost-effective drying can be achieved. Again these correlations can also be used over a wide range of parameters. Heat transfer and mass transfer aspects along with the drying kinetics can also be analyzedwith the knowledge on properties of different samples or levels of moisture contents during the drying operation.

Finally, it can also be suggested that the developed correlations can be used for the industrial drying purpose with a suitable scale-up factor. Otherwise, the developed correlations can be considered as the basis of design for an industrial fluidized bed dryer (large scale) for optimum drying conditions.

Taguchi method is applied successfully to determine optimal drying conditions for samples in the present work. The results are validated by running a three-factor, four-level experimental design. The drying time, temperature, and velocity during the process are also observed. Thus, itcan be said that the present study will contribute to the further scale-up of drying processes in the food, biochemistry, and medical industries.

The optimization of the drying operation in a fluidized bed dryer with inert particles is also performed using Taguchi method. From Taguchi analysis, it is seen that the optimum operating condition to achieve the lowest product moisture content and the highest drying time is possible at higher air velocity and airtemperature. The addition of inert materials is seen tohelp in reducing the moisture content significantly.

ANOVA analysis indicates that the system parameters are the dominant contribution factors for analysis of moisture content. Taguchi method is thus provingto be a suitable approach to the optimization of the drying process.

Existing knowledge about the influence of thedifferent process parameters of a batch process is upgraded with these experiments therebyimproving the reliability of the drying process. This study has shown the application of Taguchi method to the evaluation of the performance of a fluidized bed dryer. The level of importance of the process parameters is also determined by using ANOVA.

Effectiveness of thefluidized bed dryer is alsoconfirmed in the present studythrough different aspects (such as loss in moisture content, shrinkage constant, drying constant, diffusivity, mass transfer kinetics and changes in physical properties of agro materials). Cost effectiveness of the fluidized bed dryer for agro materials in comparison with other types of commercial dryers makes it widely adopted. Again the design of fluidized bed dryer and studies on effects of different parameters for process optimization assures the commercial viability of the fluidized bed drying. Uses of ANN, Taguchi/ANOVA for validation of several newly developed correlations are found to be satisfactory. Again proper design of fluidized bed dryer and studies on effects of different parameters for process optimization assures the commercial viability of the fluidized bed drying.

6.2. Overall Conclusions

With respect to above discussions the overall conclusion can be written as follows.

- ❑ The results of the tests on the FBD taken at 10 minutes interval ascertain its efficiency and cost effectiveness.
- ❑ In this work the design and fabrication procedure for a low cost fluidized bed has been demonstrated. Thus, it can be inferred that the weights of different samples affect the fluidization process, because grains with higher weights show less resistance to air flow in the system.
- ❑ In addition to that, increasing the airflow speed increases the drying rate but also increases the power consumption in the system.
- ❑ Smaller grains show high resistance to airflow thereafter reducing the fan outputs and also increasing the amount of moisture reduced in the grains by the hot air giving higher power efficiency in wheat than in rice.
- ❑ A fluidized bed dryer can be competitive with other convectional drying methods especially at high moisture level and low energy consumption. Drying on fluidized bed is a reliable and economical method for drying of light weighted grains.
- ❑ The developed low cost portable fluidized bed dryer can be recommended for farmers who can use it at the domestic level by which farmers can store their crops for selling or for personal uses.

6.3. Future Work

The following works can be carried out further.

- Heat transfer aspects in turn heat transfer coefficients for hot air or feed sample can be calculated using fluidized bed dryer.
- Drying can be carried out at different pressures by providing a pressure sensor to the fluidizer or in other words it can be said that effect of pressure on drying rate can be studied.
- Materials other than the crops can also be studied in the fluidized bed dryer.

- The developed correlations can be validated against other methods such as Statistical Analysis and/or Artificial Neural Network approach.
- CFD modeling can also be applied for the drying operation using a fluidized bed dryer.
- Maas Transfer aspects can be studied using a fluidized bed dryer.
- Studies on energy efficiency for the fluidized bed dryer can be carried out.
- Optimization studies on different process parameters such as time, velocity, temperature, particle shape/size, bed height, particle density, bed aspect ratio, distributor openings etc. can be carried out.
- Comparison on the performance of the fluidized bed dryer against other commercial dryers can be carried out.
- Diffusivities studies can be carried out for different geometries or considering shape factor for different feed samples.
- Cost analysis for the fluidized bed drying can be carried out for different drying conditions.

NOMENCLATURE:

B	:	Shrinkage Constant
C_P	:	Specific heat of the material, kJ/ kg.K
D_{eff}	:	Effective Diffusivity, m^2 s^{-1}
Dg	:	Geometrical mean diameter, mm.
d	:	Diameter of samples, m
Ea	:	Activation energy, kJ mol^{-1}
G_1	:	Free weight of bulk density container, kg
G_2	:	Weight of bulk density container with sample, kg
h_1	:	Specific enthalpy at inlet, kJ/kg
h_2	:	Specific enthalpy at outlet, kJ/kg
h_{fg}	:	Latent heat of vaporization of wheat, kJ/kg water
K_{DR}	:	Drying Rate
k	:	Drying Constant
K	:	Mass Transfer Coefficient, m/s
L	:	Length of the sample, cm
m_{da}	:	Mass flow rate, kg/s
M	:	Moisture at given time (kg/kg db)
M_c	:	Moisture content, kg
M_L	:	Moisture loss
M_o	:	Initial moisture, kg/kg d.b.
M_e	:	Equilibrium moisture content, kg/kg d.b.
M_R	:	Moisture ratio
r	:	Slab thickness, cm
R	:	Universal gas constant, $mol^{-1}K^{-1}$
S_a	:	Surface area mm^2

t	:	Drying time, minute
T_{m1}	:	Inlet measured temperature, ^0C
T_{m2}	:	Outlet measured temperature, ^0C
T	:	Absolute temperature, ^oK
T'	:	Thickness, mm
U_o	:	Velocity of the fluidizing medium, m/s
V_R	:	Volume ratio
V_b	:	Volume of bulk density container, m^3
V	:	Volume of sample, m^3
W	:	Weight of materials, kg
W_b	:	Weight of materials before drying, kg
W_d	:	Weight of materials after drying, kg
W_i	:	Initial Weight, kg
W_f	:	Final Weight, kg
W'	:	Width, mm
Δt	:	Drying time interval, minute

Greek letters

ρ	:	Density, kg/m^3
μ	:	Fluid viscosity, gm/m-s
Φ	:	Sphericity
ε	:	Porosity
θ	:	Temperature , ^0C
η	:	Drying efficiency

Subscript

b	:	Bulk
f	:	For fluid
l	:	For liquid
s	:	For solid
t	:	True
max	:	For maximum
1	:	w.r.t parameter
2	:	w.r.t properties

Abbreviations

χ^2	:	Chi-square
MSE	:	Mean Square Error
R^2	:	Correlation Coefficient
ANN	:	Artificial Neural Network
Cal	:	Calculative values
Exp	:	Experimental values
R.A.	:	Regression Analysis
RMS	:	Root Mean Square
STD	:	Standard Deviation
FBD	:	Fluidized Bed Dryer

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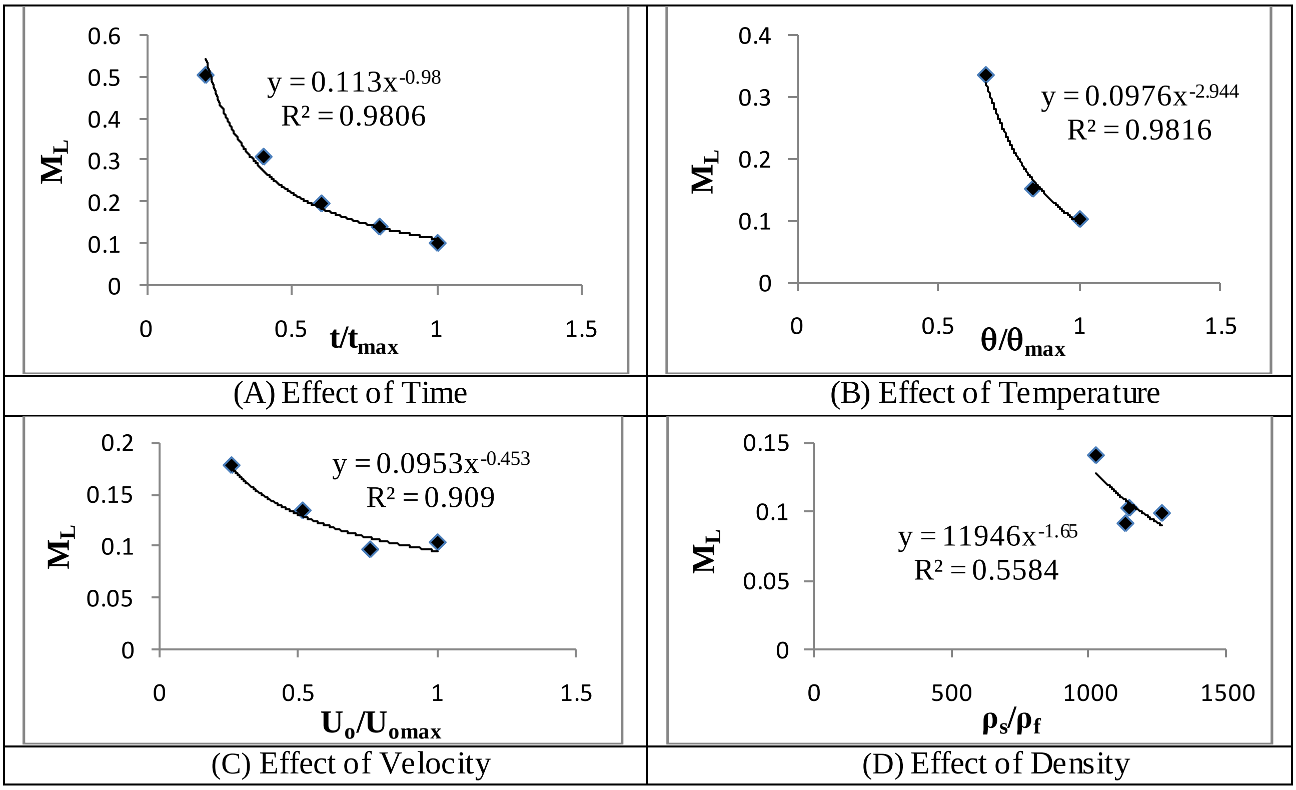
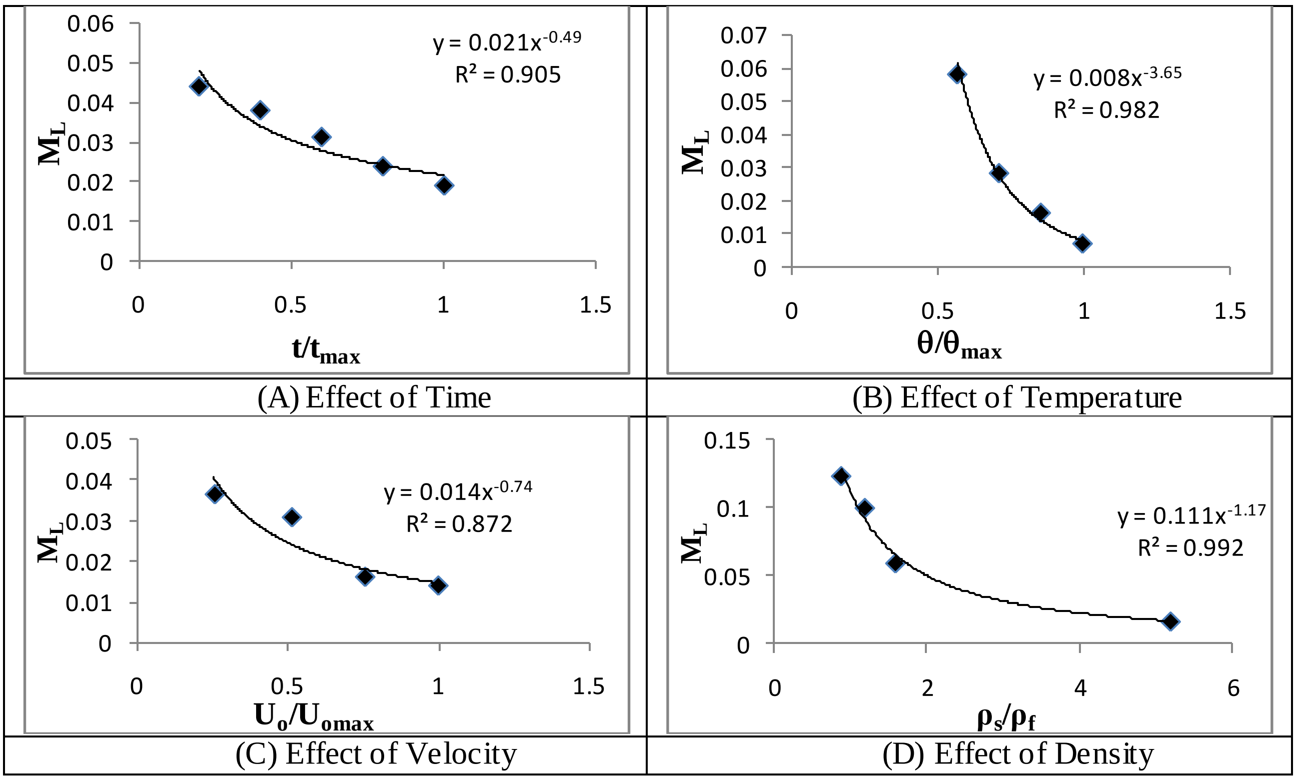
Appendix I



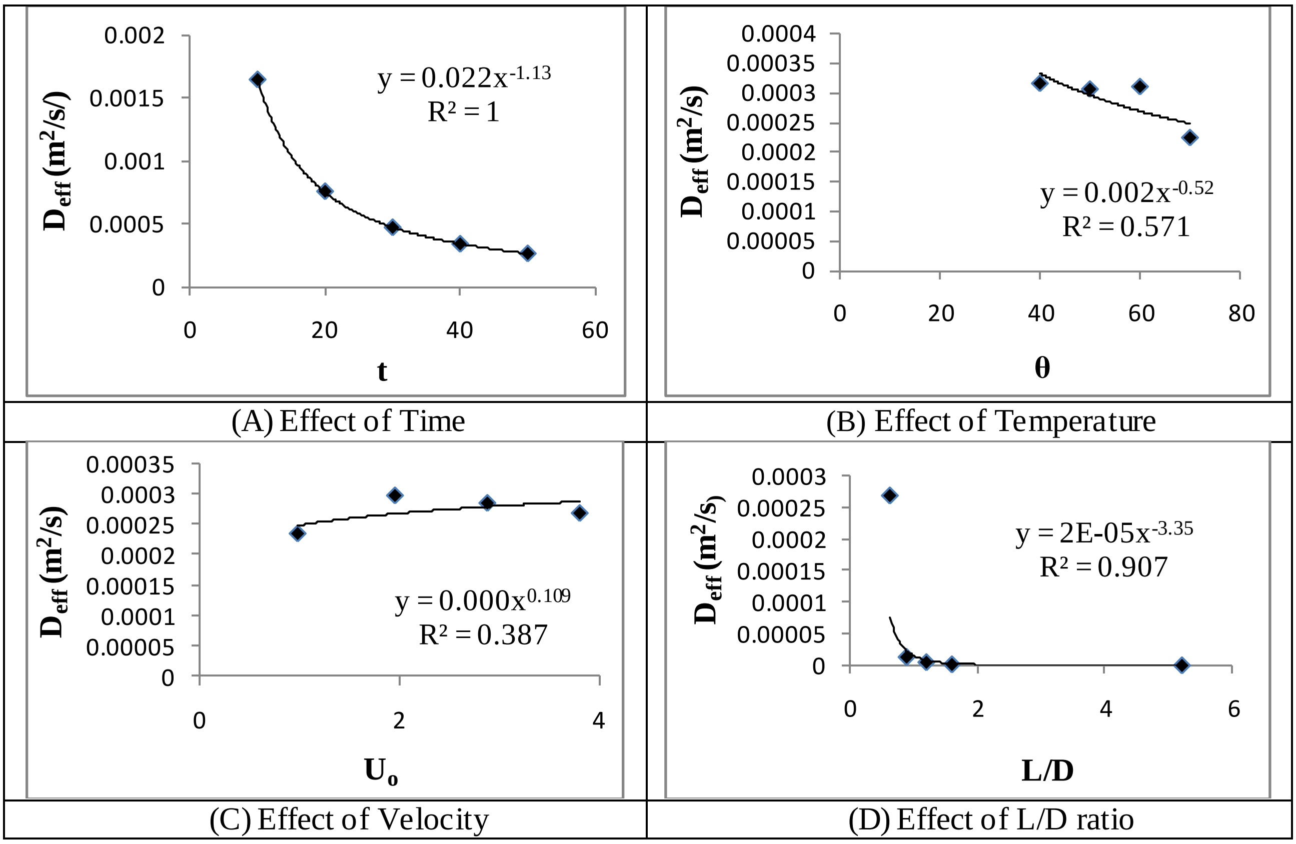
(A) Effect of Time | (B) Effect of Temperature | (C) Effect of Velocity | (D) Effect of Density

Fig. - 1: Effect of individual system parameters on the loss in moisture content for grains



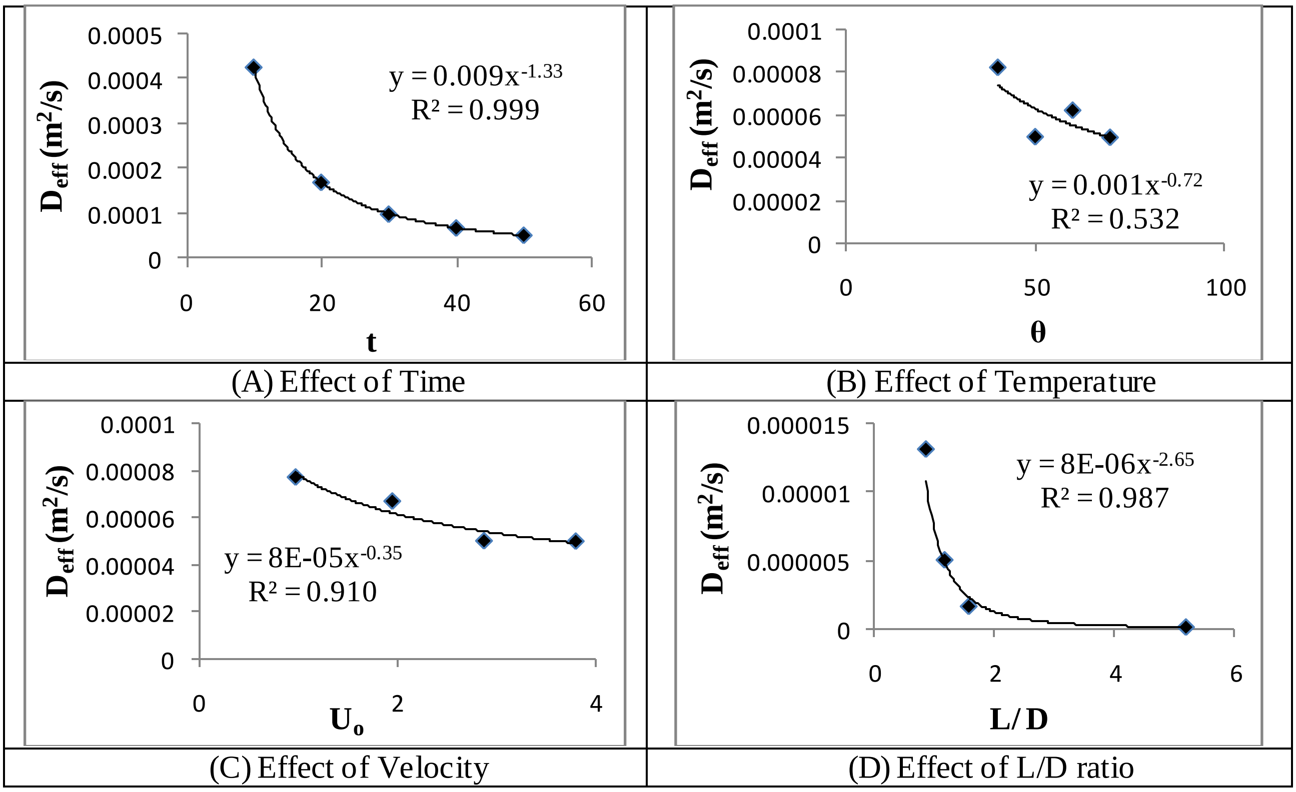
(A) Effect of Time | (B) Effect of Temperature | (C) Effect of Velocity | (D) Effect of Density

Fig. - 2: Effect of individual system parameters on the loss in moisture content for vegetable



(A) Effect of Time
(B) Effect of Temperature
(C) Effect of Velocity
(D) Effect of L/D ratio

Fig. - 3: Effect of individual system parameter on the diffusivity of mushroom



(A) Effect of Time
(B) Effect of Temperature
(C) Effect of Velocity
(D) Effect of L/D ratio

Fig. - 4: Effect of individual system parameter on the diffusivity of vegetables

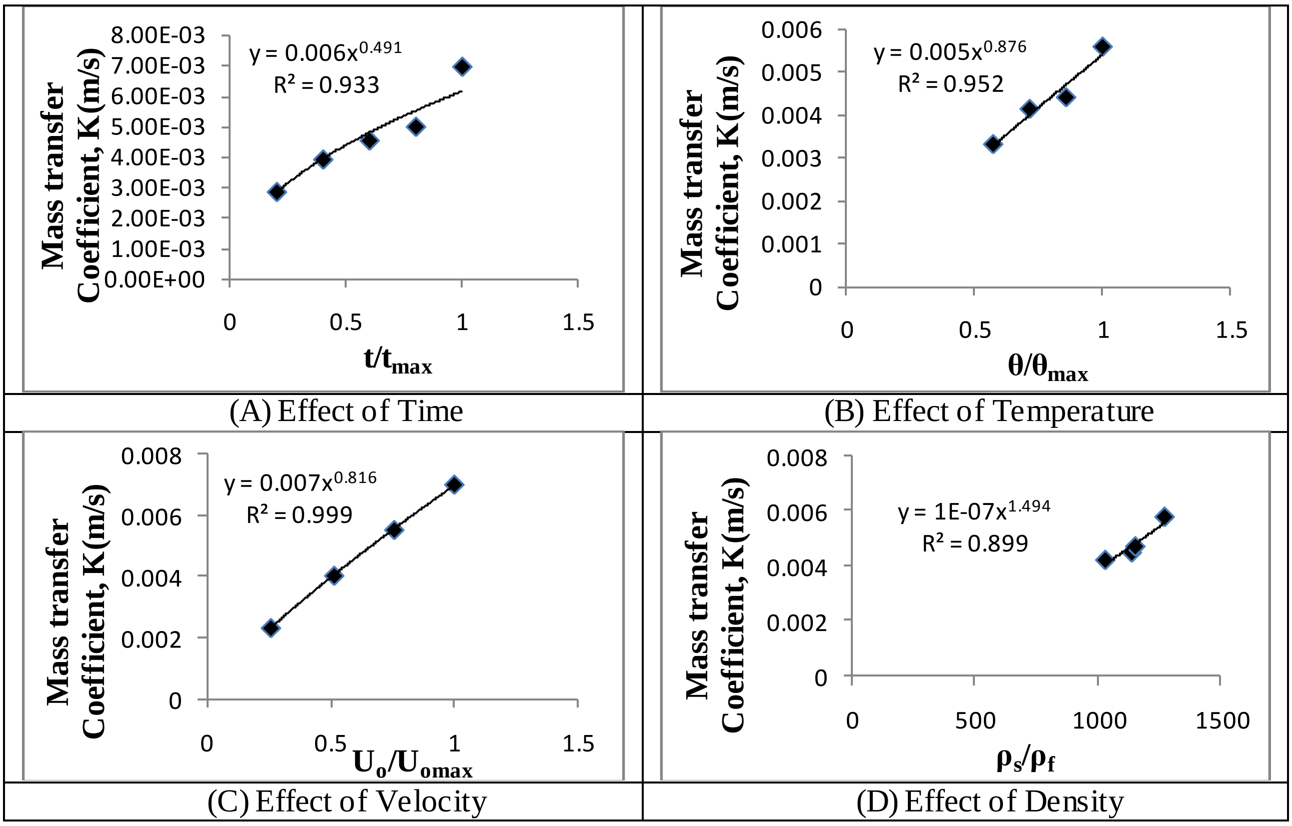


Fig. - 5: Effect of individual system parameters on the mass transfer coefficient for grains

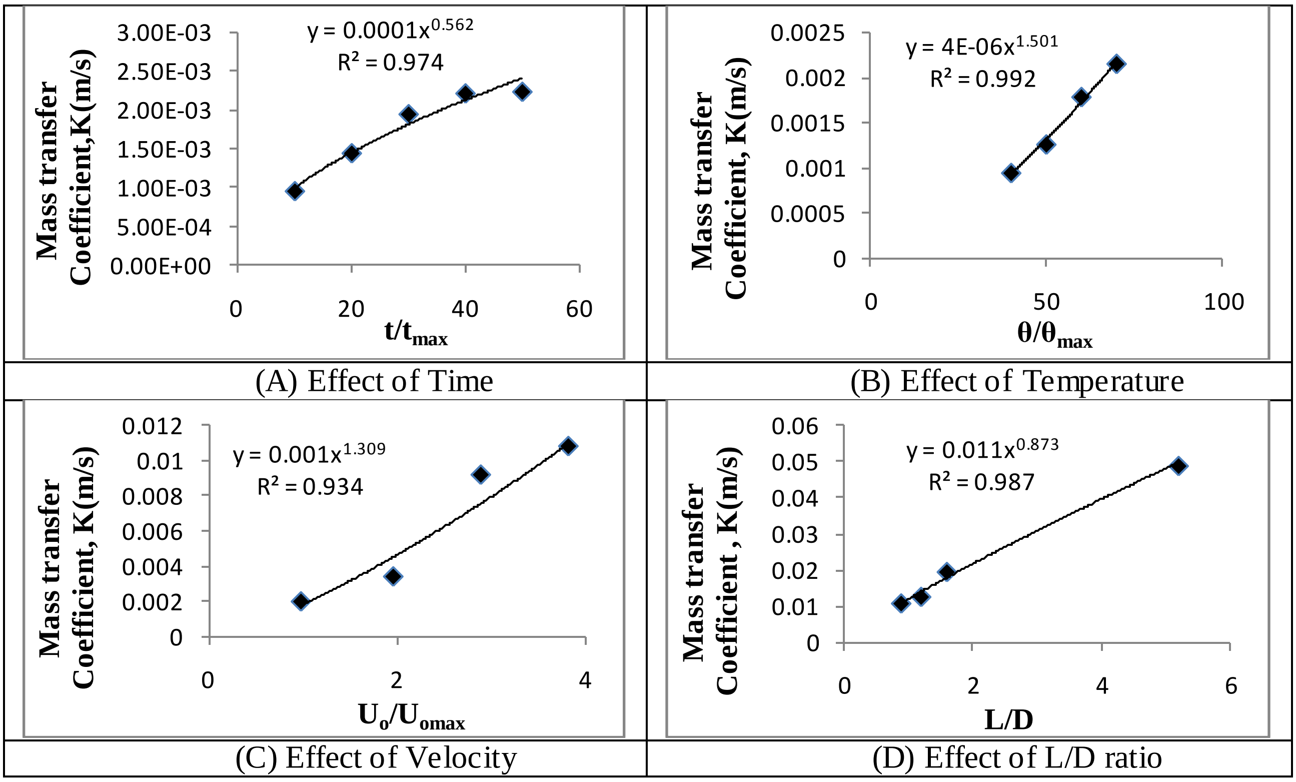
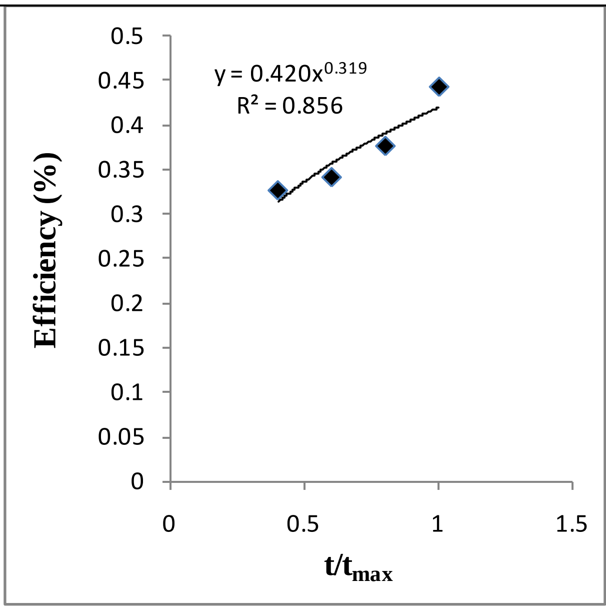
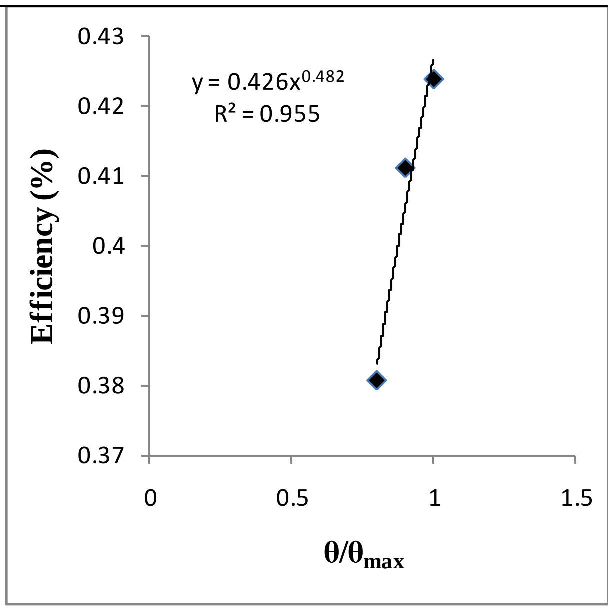


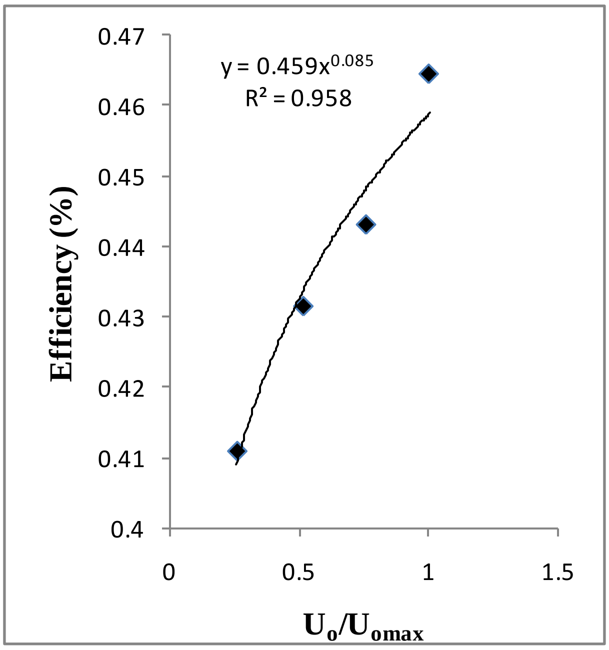
Fig. - 6: Effect of individual system parameters on the mass transfer coefficient for vegetables



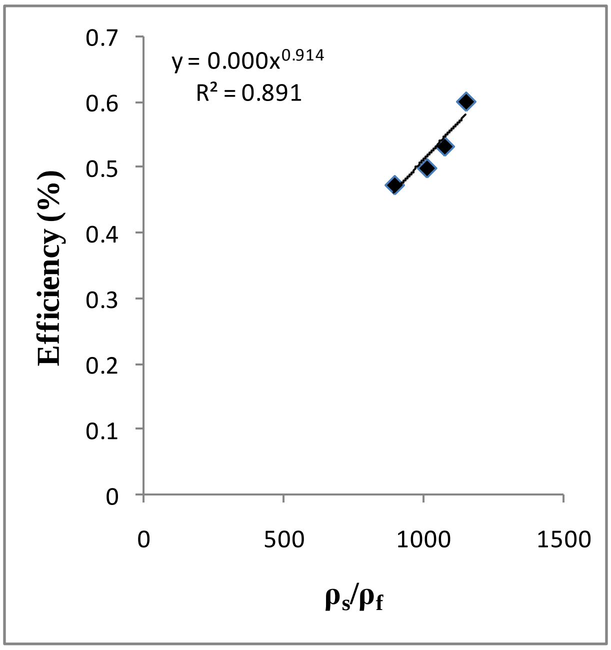
(A) Effect of Time



(B) Effect of Temperature

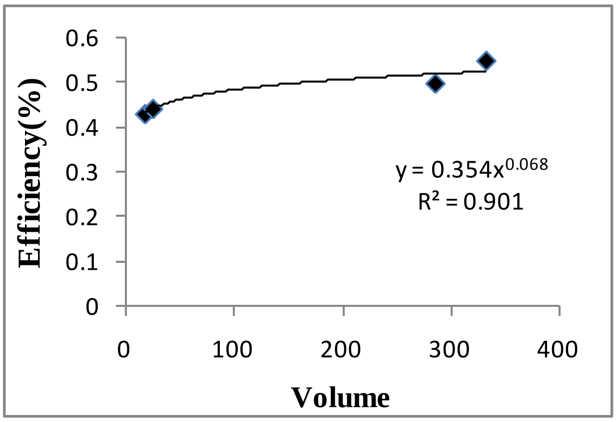


(C) Effect of Velocity

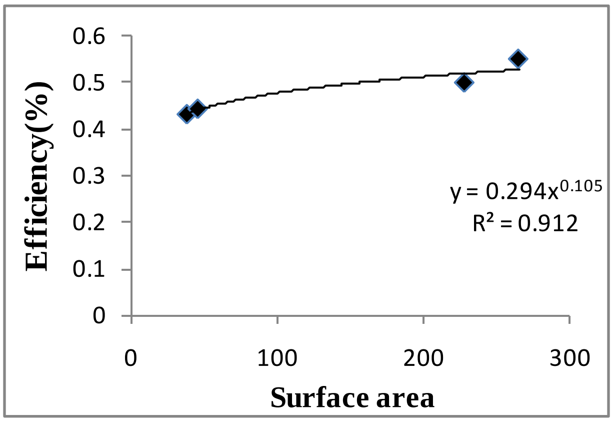


(D) Effect of Density

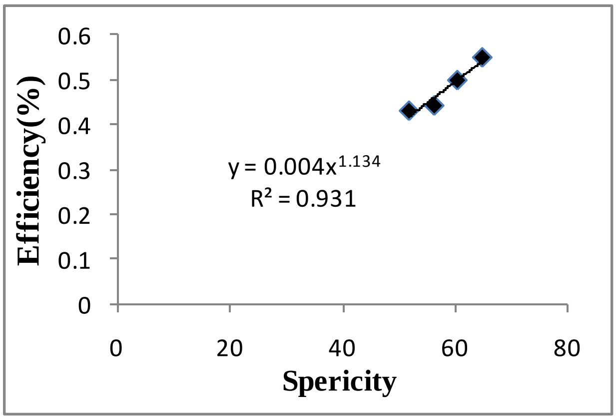
Fig. - 7: Effect of individual system parameters on the Efficiency for grains



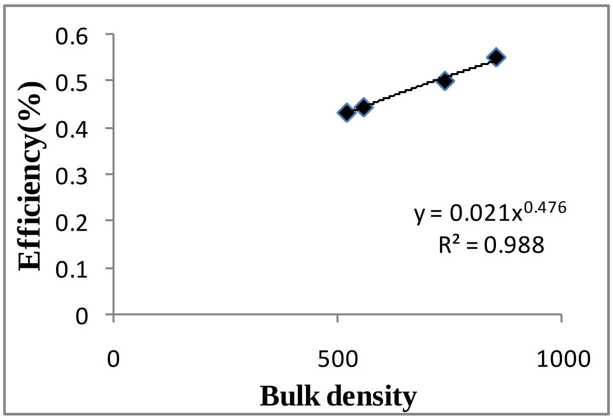
(A) Effect of Volume (V)



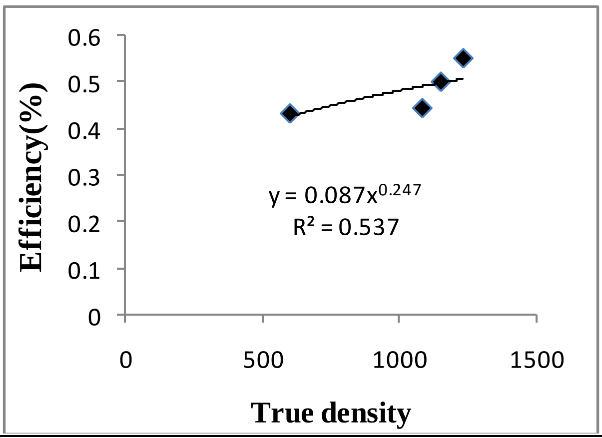
(B) Effect of Surface area(S_a)



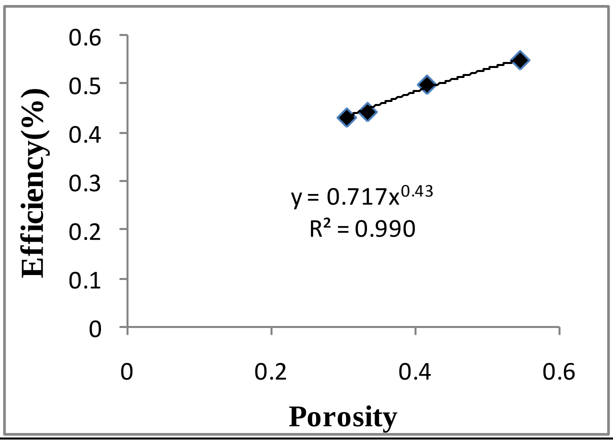
(C) Effect of Spericity (ϕ)



(D) Effect of Bulk density(ρ_b)



(E) Effect of True density (ρ_t)



(F) Effect of Porosity (ε)

Fig. - 8: Effect of physical properties on the Efficiency for grains

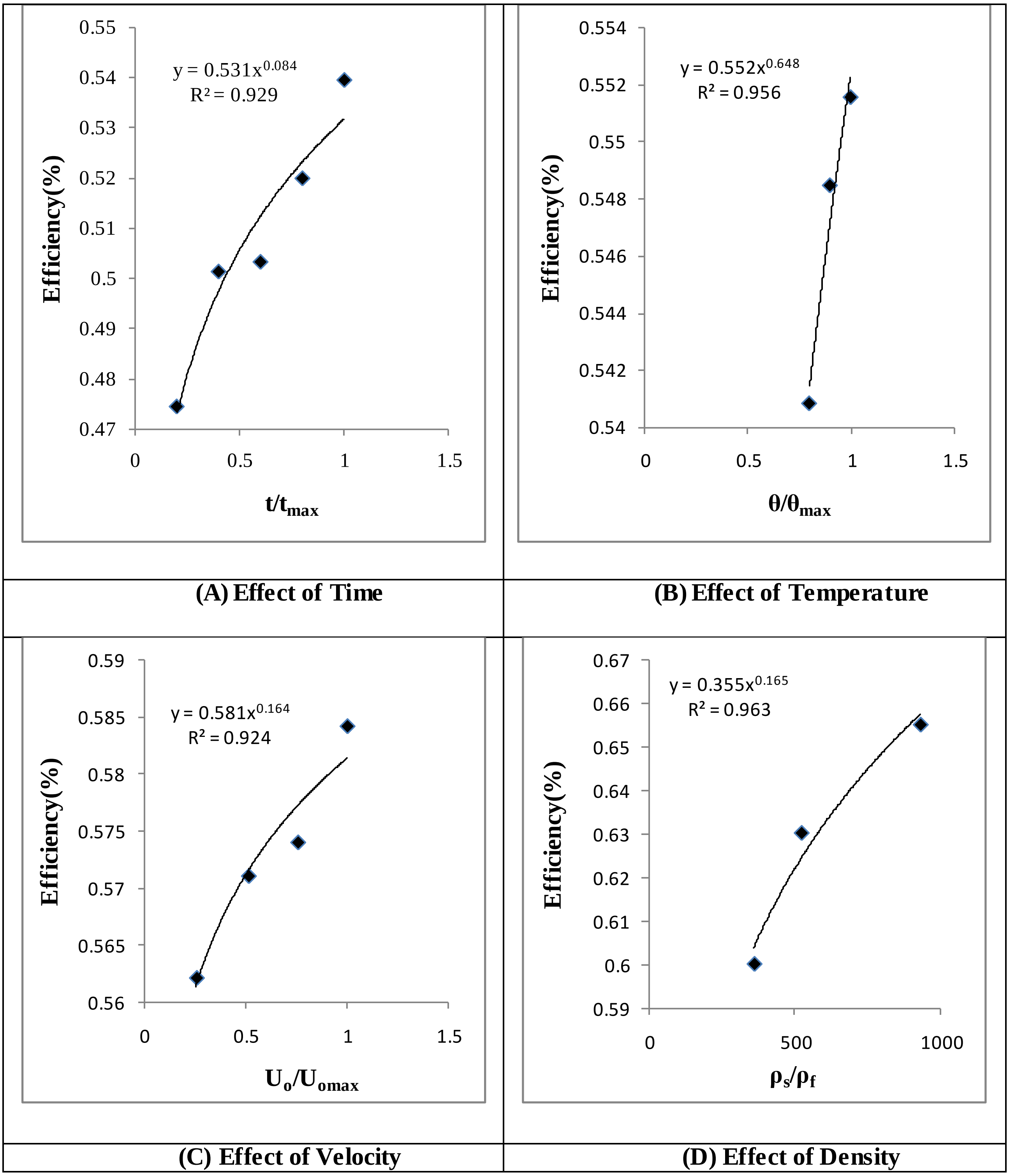
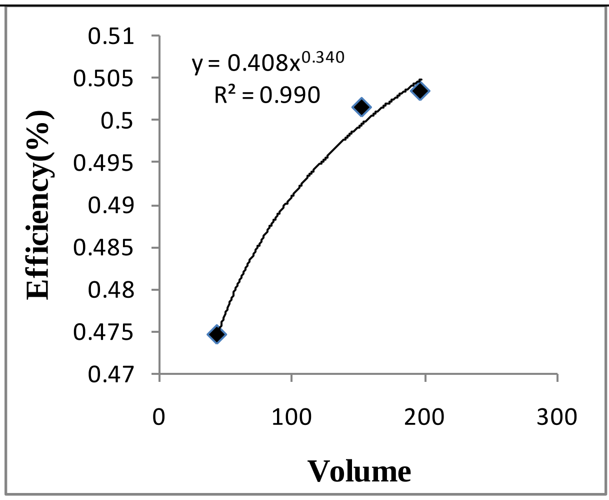
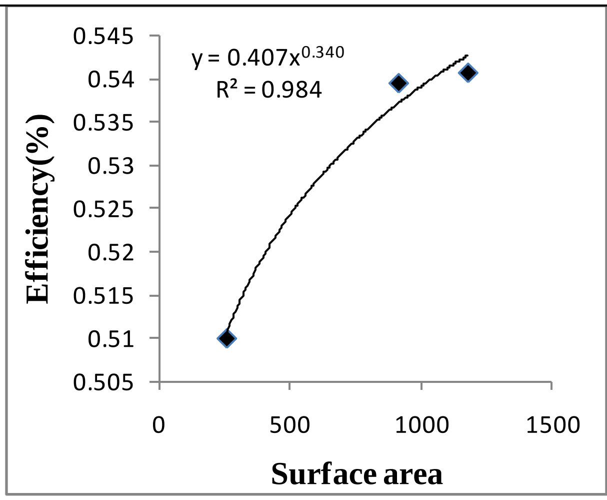


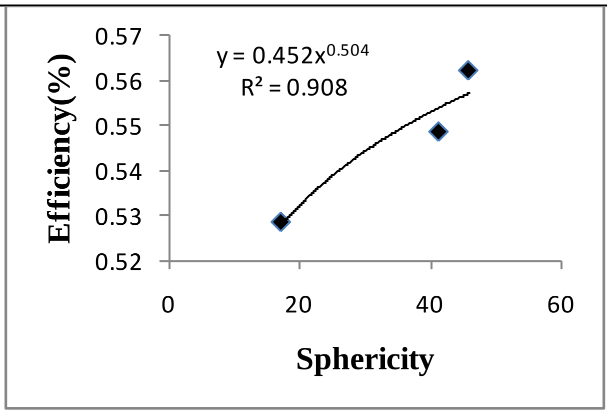
Fig. - 9: Effect of individual system parameters on the Efficiency for vegetables



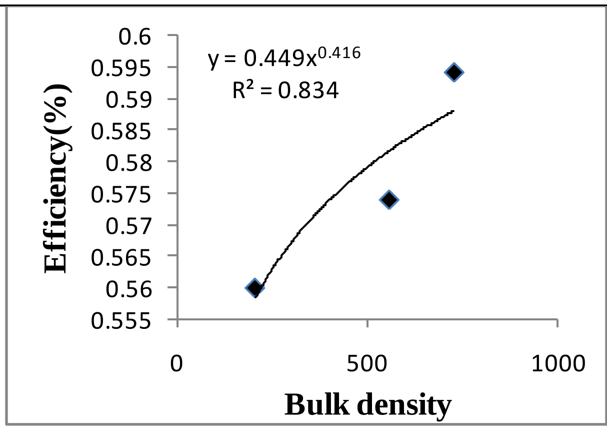
(A) Effect of Volume (V)



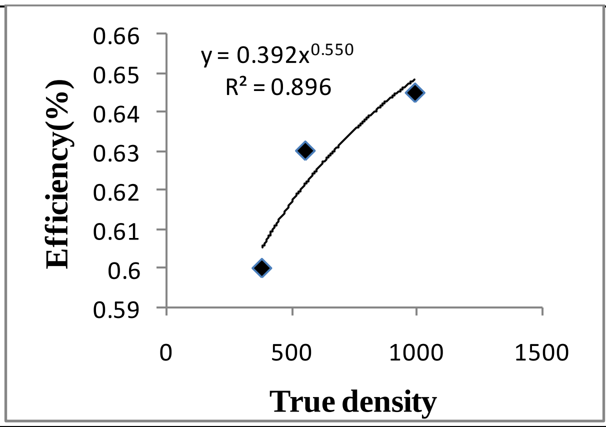
(B) Effect of Surface area(S_a)



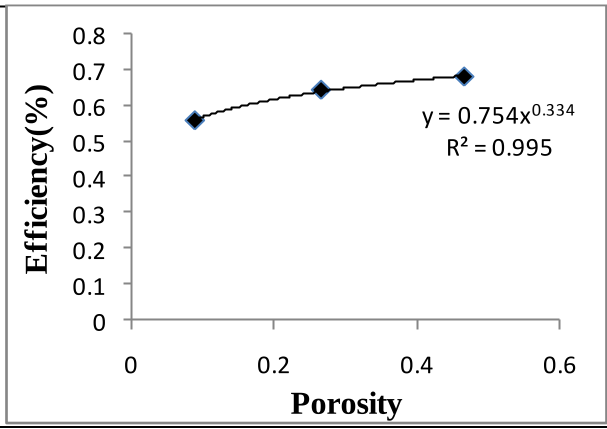
(C) Effect of Spericity (ϕ)



(D) Effect of Bulk density(ρ_b)



(E) Effect of True density (ρ_t)



(F) Effect of Porosity (ε)

Fig. - 10: Effect of physical properties on the Efficiency for vegetable

Appendix II

Table - 1: Comparison of calculated values of moisture loss against experimentally observed values with different system parameters for grains

Sl No.	t/t_{max}	θ/θ_{max}	U_o/U_{omax}	ρ_s/ρ_f	M_L-EXP	R.A.	ANN	R.A.	ANN
						M_L-CAL	M_L-CAL	%Dev.	%Dev.
1	0.2	1	1	1152.765	0.503	0.516	0.675	-2.45	8.77
2	0.4	1	1	1152.765	0.308	0.257	0.342	16.59	6.57
3	0.6	1	1	1152.765	0.197	0.171	0.230	13.13	4.28
4	0.8	1	1	1152.765	0.141	0.128	0.174	9.33	6.96
5	1	1	1	1152.765	0.102	0.102	0.139	0.02	-1.81
6	1	0.6	1	1152.765	0.336	0.348	0.406	-3.59	8.16
7	1	0.8	1	1152.765	0.151	0.177	0.226	-17.09	3.41
8	1	1	1	1152.765	0.102	0.102	0.139	0.02	-1.81
9	1	1	0.2	1152.765	0.177	0.193	0.236	-8.71	3.68
10	1	1	0.5	1152.765	0.133	0.140	0.180	-4.67	18.93
11	1	1	0.7	1152.765	0.095	0.116	0.155	-21.91	-10.72
12	1	1	1	1152.765	0.102	0.102	0.139	0.02	-1.81
13	1	1	1	1030.928	0.141	0.124	0.167	12.01	25.35
14	1	1	1	1138.707	0.091	0.104	0.142	-14.48	-14.27
15	1	1	1	1152.765	0.102	0.102	0.139	0.02	-1.81
16	1	1	1	1271.79	0.099	0.087	0.119	12.12	-5.08

Table - 2: Comparison of calculated values of moisture loss against experimentally observed values with different system parameters for vegetables

Sl No.	t/t_{max}	θ/θ_{max}	U_o/U_o	L/D	M_L-EXP	R.A.	ANN	R.A.	ANN
						M_L-CAL	M_L-CAL	%Dev.	%Dev.
1	0.2	1	1	1.2	0.044	0.042	0.043	3.66	1.38
2	0.4	1	1	1.2	0.038	0.027	0.026	9.15	3.14
3	0.6	1	1	1.2	0.031	0.021	0.019	4.10	9.29
4	0.8	1	1	1.2	0.024	0.017	0.015	8.88	6.27
5	1	1	1	1.2	0.016	0.015	0.013	9.26	20.41
6	1	0.5714	1	1.2	0.058	0.049	0.051	15.43	11.52
7	1	0.7143	1	1.2	0.028	0.030	0.030	-7.69	-5.02
8	1	0.8571	1	1.2	0.016	0.021	0.019	-6.24	-16.24
9	1	1	0.2	1.2	0.007	0.016	0.014	-12.86	-9.23
10	1	1	0.5	1.2	0.037	0.043	0.044	-17.98	-21.24
11	1	1	0.7	1.2	0.031	0.043	0.044	-37.55	-41.03

12	1	1	1	1.2	0.016	0.015	0.013	9.26	20.41
13	1	1	1	1.2	0.014	0.015	0.013	-4.76	8.11
14	1	1	1	0.8	0.123	0.128	0.154	-3.69	-24.97
15	1	1	1	1.2	0.100	0.089	0.101	11.20	-1.41
16	1	1	1	1.6	0.059	0.062	0.068	-5.37	-14.27
17	1	1	1	5.2	0.016	0.015	0.013	9.26	20.41

Table - 3: Variation of volume ratios and moisture ratios of Red kidney bean for different aspect ratio

Time (min)	Weight (kg)	L_1 (mm)	W_1 (mm)	h_1 (mm)	V_1 (mm^3)	L_2 (mm)	W_2 (mm)	h_2 (mm)	V_2 (mm^3)	Avg. Volume	V_R	M_R
0	182	14.7	8.9	7.5	981.22	17.7	9.1	10	1610.7	525.74	1	0
10	170	14.3	8.5	5.3	644.21	17.6	8.7	9	1378.08	411.52	0.783	0.143
20	135	13.7	8.1	5	554.85	16.5	8.1	8.6	1149.39	347.48	0.661	0.560
30	115	13.3	8	4.5	478.8	16	8	7	896	281.16	0.535	0.798
40	105	13.1	7.6	4	398.24	15.5	7.8	6	725.4	230.58	0.439	0.917
50	98	13	7.5	3.5	341.25	15	7.2	5.5	594	192.59	0.366	1

Table - 4: Variation of volume ratios and moisture ratios of Bean seed for different aspect ratios

Time (min)	Weight (kg)	L_1 (mm)	W_1 (mm)	h_1 (mm)	V_1 (mm^3)	L_2 (mm)	W_2 (mm)	h_2 (mm)	V_2 (mm^3)	Avg. Volume	V_R	M_R
0	182	14.1	8.6	5	606.3	12.6	8.8	8	887.04	304.54	1	0
10	162	13.7	8.2	4.5	505.53	12.3	8.7	7.5	802.57	267.32	0.878	0.235
20	125	13.2	7.8	4	411.84	12	7.7	7	646.8	217.06	0.713	0.671
30	115	12.7	7.6	3.3	318.51	11.7	7.4	6	519.48	172.61	0.567	0.788
40	100	12.3	7.4	3	273.06	11.4	7.3	6	499.32	159.41	0.523	0.965
50	97	11.2	7.1	2	159.04	11.1	7.2	5	399.6	116.38	0.382	1

Table - 5: Variation of volume ratios and moisture ratios of Wheat for different aspect ratios

Time (min)	Weight (kg)	L_1 (mm)	W_1 (mm)	h_1 (mm)	V_1 (mm^3)	L_2 (mm)	W_2 (mm)	h_2 (mm)	V_2 (mm^3)	Avg. Volume	V_R	M_R
0	175	6.8	3.9	3.9	103.42	7.3	4.3	4.3	134.97	50.86	1	0
10	107	6.6	3.8	3.7	92.79	6.8	3.9	4	106.08	42.71	0.840	0.602
20	88	6.5	3.7	3.5	84.17	6.7	3.8	3.9	99.29	39.57	0.778	0.770
30	78	6.2	3.5	3.4	73.78	6.4	3.8	3.7	89.98	35.53	0.699	0.858
40	69	6.1	3.5	3.2	68.32	6.3	3.7	3.7	86.24	33.65	0.662	0.938
50	62	5.9	3.4	3	60.18	6	3.5	3.5	73.5	29.33	0.577	1

Table - 6: Variation of volume ratios and moisture ratios of Rice for different aspect ratios

Time (min)	Weight (kg)	L_1 (mm)	W_1 (mm)	h_1 (mm)	V_1 (mm^3)	L_2 (mm)	W_2 (mm)	h_2 (mm)	V_2 (mm^3)	Avg. Volume	V_R	M_R
0	162	5.9	4.3	3.5	88.79	6.1	3.9	4	95.16	39.59	1	0
10	140	5.8	4.1	3.2	76.09	6	3.6	3.8	82.08	34.31	0.867	0.293
20	125	5.7	3.5	3.2	63.84	5.9	3.6	3.5	74.34	30.23	0.764	0.493
30	115	5.5	3.4	3	56.1	5.8	3.5	3.1	62.93	26.28	0.664	0.627
40	91	5.1	3.3	2.5	42.07	5.6	3.4	2.8	53.31	21.43	0.541	0.947
50	87	5	3.2	2	32	5.5	3.2	2	35.2	15.58	0.394	1

Table - 7: Variation of volume ratios and moisture ratios of Ladies finger for different aspect ratios

Time (min)	Weight (kg)	h_1 (mm)	A_1 (mm^2)	V_1 (mm^3)	h_2 (mm)	A_2 (mm^2)	V_2 (mm^3)	Avg. Volume	V_R	M_R
0	154	25	158.5	3962.5	31	181.5	5626.5	2450.37	1	0
10	132	24	150	3600	30	176	5280	2271.5	0.927	0.344
20	115	22	137.75	3030.5	29	155	4495	1927.37	0.787	0.609
30	109	22	121.12	2664.75	28	135	3780	1651.93	0.674	0.703
40	95	21	101.25	2126.25	27	132.75	3584.25	1467.56	0.599	0.922
50	90	20	82.87	1657.5	26	121.12	3149.25	1238.46	0.505	1

Table - 8: Variation of volume ratios and moisture ratios of Ivy gourd (Tundli) for different L/D ratios

Time (min)	Weight (kg)	L_1 (mm)	D_1 (mm)	V_1 (mm^3)	L_2 (mm)	D_2 (mm)	V_2 (mm^3)	Avg. Volume	V_R	M_R
0	170	70	33	59840.55	65	30	45922.5	26464.51	1	0
10	150	69	31	52052.57	64	28	39388.16	22883.18	0.865	0.438
20	135	65	30	45922.5	63	26	33431.58	19860.77	0.750	0.745
30	128	62	30	43803	61	25	29928.13	18454.28	0.697	0.894
40	125	60	29	39611.1	60	25	29437.5	17283.4	0.653	0.957
50	123	58	26	30778.28	58	24	26225.28	14271.39	0.539	1

Table - 9: Variation of volume ratios and moisture ratios of String beans (Barbatti) for different L/D ratios

Time (min)	Weight (kg)	L_1 (mm)	D_1 (mm)	V_1 (mm^3)	L_2 (mm)	D_2 (mm)	V_2 (mm^3)	Avg. Volume	V_R	M_R
0	175	72	14	11077.92	61	12	6895.44	4511.59	1	0
10	140	70	13	9286.55	59	11	5604.11	3740.16	0.829	0.428
20	125	62	13	8225.23	57	10	4474.5	3191.68	0.707	0.625
30	105	61	12	6895.44	55	9.7	4062.33	2755.62	0.611	0.875
40	100	60	11	5699.1	52	9.5	3684.01	2361.15	0.523	0.938
50	95	59	9.3	4005.78	50	9.3	3394.73	1864.95	0.413	1

Table - 10: Drying and Shrinkage Constants for different samples

Sl No.	Drying Kinetics (Time vs. V_R)	Drying Kinetics (M_R vs. V_R)	Drying Constant	Shrinkage Constant
Red kidney bean	$y = 0.979e^{-0.02x}$ $R^2 = 0.998$	$y = 0.977e^{-0.87x}$ $R^2 = 0.942$	-0.02	-0.87
Bean seed	$y = 1.030e^{-0.01x}$ $R^2 = 0.982$	$y = 1.061e^{-0.82x}$ $R^2 = 0.881$	-0.01	-0.82
Wheat	$y = 0.964e^{-0.01x}$ $R^2 = 0.978$	$y = 1.048e^{-0.48x}$ $R^2 = 0.862$	-0.01	-0.48
Rice	$y = 1.050e^{-0.01x}$ $R^2 = 0.964$	$y = 1.078e^{-0.84x}$ $R^2 = 0.908$	-0.01	-0.84
Ladies finger	$y = 1.031e^{-0.01x}$ $R^2 = 0.992$	$y = 1.085e^{-0.66x}$ $R^2 = 0.915$	-0.01	-0.66
Ivy gourd	$y = 0.98e^{-0.01x}$ $R^2 = 0.977$	$y = 1.042e^{-0.51x}$ $R^2 = 0.869$	-0.01	-0.51
String beans	$y = 0.998e^{-0.01x}$ $R^2 = 0.994$	$y = 1.071e^{-0.77x}$ $R^2 = 0.888$	-0.01	-0.77

Table - 11: The outputs obtained through Regression Analysis and ANN-analysis for different samples

Sl No.	Out Puts	Moisture Loss for grains		Moisture Loss for vegetables	
		R.A.	**ANN**	**R.A.**	**ANN**
1	a	-0.98	0. 93	-0.07	0.45
2	b	-2.94	1.14	-0.22	0.44
3	c	-0.45	1.03	-0.15	0.44
4	d	-1.65	1.03	-0.44	0.43
5	K'	1517	1219	120.63	103.99
6	n	1.02	1.05	1.11	0.51

Table - 12: Comparisons of calculated values of drying characteristics against the experimentally observed values for different samples

		R.A.					ANN				
Sl No.	**SAMPLES**	**Std. Dev.**	**Mean Dev.**	χ^2	R^2	**MSE**	**Std. Dev.**	**Mean Dev.**	χ^2	R^2	**MSE**
1	Grains	11.313	-0. 602	0.031	0.985	0.0004	14.189	-32.744	0.209	0.988	0.0041
2	Vegetables	10.195	-0.012	0.026	0.963	$0.47E^{-05}$	48.026	-1.33	0.089	0.993	0.056

Table - 13: The developed mass transfer coefficient (m/s) for different samples

Sl No.	Grains	Kinetic Equation	Vegetables	Kinetic Equation
1	Wheat	$K= 0.0034\ e^{107.74/\theta}$	Mushroom	$K= 0.0341\ e^{862.79/\theta}$
2	Bean	$K= 0.0023\ e^{107.75/\theta}$	Ivy gourd	$K= 0.0004\ e^{1093.4/\theta}$
3	Rice	$K= 0.0014\ e^{107.86/\theta}$	Ladies finger	$K= 6E\text{-}07\ e^{2435.4/\theta}$
4	Red kidney bean	$K= 0.0012\ e^{108.24/\theta}$		

Table - 14: Comparison of calculated values of diffusivity against experimentally observed values with different system parameters for grains

Sl No.	t (min)	θ (°C)	U_o (m/s)	L/D		Diffusivity by R.A.		by ANN analysis	
					measured $*10^4(m^2/s)$	$*10^4(m^2/s)$	%Dev.	$*10^4(m^2/s)$	%Dev.
1	10	50	3.8	0.628	16.0	13.312	16.80	9.7	39.38
2	20	50	3.8	0.628	7.0	6.97	0.43	5.4	22.86
3	30	50	3.8	0.628	4.0	4.774	-19.35	3.8	5.00
4	40	50	3.8	0.628	3.0	3.65	-21.67	.30	90.00
5	50	50	3.8	0.628	2.0	2.964	-48.20	2.5	-25.00
6	50	40	3.8	0.628	3.0	3.262	-8.73	2.8	6.67
7	50	50	3.8	0.628	3.0	2.964	1.20	2.5	16.67
8	50	60	3.8	0.628	3.0	2.74	8.67	2.2	26.67
9	50	70	3.8	0.628	2.0	2.565	-28.25	2.0	0.00
10	50	50	0.97	0.628	2.0	2.622	-31.10	1.8	10.00
11	50	50	1.95	0.628	2.0	2.791	-39.55	2.1	-5.00
12	50	50	2.87	0.628	2.0	2.89	-44.50	2.3	-15.00
13	50	50	3.8	0.628	2.0	2.964	-48.20	2.5	-25.00
14	50	50	3.8	0.628	2.0	2.964	-48.20	2.5	-25.00
15	50	50	3.8	0.89	1.0	1.129	-12.90	1.1	-10.00
16	50	50	3.8	1.2	0.497	0.494	0.60	0.5	-0.60
17	50	50	3.8	1.6	0.254	0.223	12.20	0.3	-18.11
18	50	50	3.8	5.2	0.0112	0.0085	24.11	0.017	-51.79

Table - 15: Comparison of calculated values of diffusivity against experimentally observed values with different system parameters for vegetables

Sl No.	t (min)	θ (°C)	U_o (m/s)	L/D		Diffusivity by R.A.		by ANN analysis	
					measured $*10^4(m^2/s)$	$*10^4(m^2/s)$	%Dev.	$*10^4(m^2/s)$	%Dev.
1	10	50	3.8	1.2	4.0	4.378	-9.45	2.798	30.05
2	20	50	3.8	1.2	1.68	1.77	-5.36	1.276	24.05
3	30	50	3.8	1.2	0.97	1.043	-7.53	0.806	16.90
4	40	50	3.8	1.2	0.661	0.71	-7.41	0.582	11.97

5	50	50	3.8	1.2	0.497	0.53	-6.64	0.452	9.07
6	50	40	3.8	1.2	0.824	0.626	24.03	0.548	33.45
7	50	50	3.8	1.2	0.497	0.535	-7.65	0.452	9.07
8	50	60	3.8	1.2	0.622	0.47	24.44	0.386	37.96
9	50	70	3.8	1.2	0.495	0.42	15.15	0.338	31.80
10	50	50	0.97	1.2	0.772	0.85	-10.10	0.737	4.53
11	50	50	1.95	1.2	0.669	0.67	-0.15	0.574	14.13
12	50	50	2.87	1.2	0.499	0.58	-16.23	0.500	-0.12
13	50	50	3.8	1.2	0.497	0.535	-7.65	0.452	9.07
14	50	50	3.8	0.89	1.0	1.164	-16.40	0.930	7.04
15	50	50	3.8	1.2	0.497	0.535	-7.65	0.452	9.07
16	50	50	3.8	1.6	0.254	0.25	1.57	0.226	11.13
17	50	50	3.8	5.2	0.0112	0.01	10.71	0.013	-17.23

Table - 16: Effective moisture Diffusivity (m^2/s) measured at different drying times for various samples

time (min)	Mushroom	Ivy gourd	String beans	Radish	Ladies finger
10	0.0016	$4.330x10^{-05}$	$2.809x10^{-0}5$	0.0010	0.0005
20	0.0007	$1.710x10^{-05}$	$9.393x10^{-06}$	0.0004	0. 0001
30	0.0004	$9.860x10^{-06}$	$4.386x10^{-06}$	0.0002	$9.008x10^{-05}$
40	0.0003	$6.718x10^{-06}$	$2.232x10^{-06}$	0.0001	$4.799x10^{-05}$
50	0.0002	$5.056x10^{-06}$	$1.118x10^{-06}$	0.0001	$2.537x10^{-05}$

Table - 17: Activation energy (KJ/mol) measured at different drying times for various samples

time (min)	Mushroom	Ivy gourd
10	5162.348	26372.959
20	6210.782	26589.131
30	7292.472	27686.619
40	8261.088	29440.936
50	9037.644	30920.881

Table - 18: Comparisons of calculated values of drying characteristics against the experimentally observed values for different samples

	Regression analysis		ANN analysis	
Sample	**Std. Dev.**	**Mean Dev.**	**Std. Dev.**	**Mean Dev.**
Mushroom	11.532	17.999	23.131	$2.416*10^{-05}$
Vegetables	12.097	16.999	13.824	0.00008

Table - 19: The outputs obtained through Regression Analysis and ANN-analysis for different samples

	Mushroom		Vegetables	
Parameter	**R.A.**	**ANN**	**R.A.**	**ANN**
a	-1.13	-1.001	-1.33	-1.15
b	-0.52	-0.76	-0.72	-0.88
c	0.109	0.25	-0.35	-0.365
d	-3.35	-2.7	-2.65	-2.45
K	0.015	0.0228	0.358	0.283
n	0.826	0.856	0.982	0.985

Table - 20: Mass transfer coefficients determined for various samples

Samples	K (m/s)
Mushroom	$K = 0.0341\, e^{862.79/\theta}$
Ivy gourd	$K = 0.0004\, e^{1093.4/\theta}$

Table - 21: Mass transfer coefficient correlated from diffusivity dimensionless numbers for different grains/pulses

Sl No.	Samples	θ (°C)	D_{eff}. (m^2/s)	Re No.	Sc No.	Sh No.	K (m/s)
1	Red kidney bean	313	8.897E-08	672	190.721	97.344	0.0029
2	Red kidney bean	323	1.438E-07	636	124.654	82.291	0.0039
3	Red kidney bean	333	1.812E-07	603	104.264	75.574	0.0046
4	Red kidney bean	343	2.112E-07	572	94.307	71.216	0.0050
5	Red kidney bean	313	3.498E-07	545	59.805	59.795	0.0060
6	Bean seed	323	2.027E-08	448	837.160	129.497	0.00022
7	Bean seed	333	2.062E-08	428	869.524	127.55	0.00022
8	Bean seed	343	2.582E-08	402	731.873	117.383	0.00025
9	Bean seed	313	2.687E-08	382	741.116	114.813	0.00026
10	Bean seed	323	2.932E-08	363	713.42	110.636	0.00027
11	Wheat	333	2.557E-08	224	663.456	181	0.0005
12	Wheat	343	4.040E-08	212	443.906	72.2	0.0007
13	Wheat	313	4.649E-08	201	406.480	68.4	0.0008
14	Wheat	323	5.159E-08	191	386.061	65.5	0.0008
15	Wheat	333	5.447E-08	182	384.020	63.8	0.0009
16	Rice	343	5.471E-08	448	310.188	93.3	0.0010
17	Rice	313	8.171E-08	424	219.475	81	0.0013
18	Rice	323	1.071E-07	402	176.405	73.4	0.0016
19	Rice	333	1.409E-07	382	141.338	66.5	0.0019
20	Rice	343	1.695E-07	363	123.415	62	0.0021

Table - 22: Mass transfer coefficient correlated from diffusivity dimensionless numbers for different vegetables

Sl No.	Samples	θ (°C)	D_{eff}. (m^2/s)	Re No.	Sc No.	Sh No.	K, m/s
1	Ivy gourd	313	1.159E-07	3806.718	146.459	212.388	0.00095
2	Ivy gourd	323	2.182E-07	3601.896	82.182	170.730	0.0014
3	Ivy gourd	333	3.459E-07	3417.989	54.644	145.359	0.0019
4	Ivy gourd	343	4.251E-07	3242.972	46.854	134.582	0.0022
5	Ivy gourd	313	4.365E-07	3087.954	47.931	132.314	0.0022
6	String beans	323	4.40E-07	1119.623	38.534	74.136	0.0013
7	String beans	333	2.73E-06	1059.381	6.577	40.238	0.0042
8	String beans	343	4.901E-06	1005.291	3.856	32.865	0.0062
9	String beans	313	6.226E-06	953.815	3.200	30.101	0.0072
10	String beans	323	6.471E-06	908.222	3.233	29.474	0.0073
11	Radish	333	1.23E-05	5150.265	1.377	52.958	0.0296
12	Radish	343	1.805E-05	4873.153	0.993	46.251	0.0379
13	Radish	313	1.891E-05	4624.339	1.000	45.149	0.0388
14	Radish	323	3.837E-05	4387.550	0.519	35.427	0.0617
15	Radish	333	6.093E-05	4177.820	0.343	30.160	0.0835
16	Ladies Finger	343	1.827E-06	447.849	9.289	29.320	0.0021
17	Ladies Finger	313	1.598E-05	423.752	1.122	14.200	0.0091
18	Ladies Finger	323	2.597E-05	402.116	0.728	11.990	0.0124
19	Ladies Finger	333	4.979E-05	381.526	0.400	9.586	0.0191
20	Ladies Finger	343	9.317E-05	363.289	0.225	7.731	0.0288

Table -23: Comparison of calculated values against the experimental values of mass transfer coefficient for grains and vegetables.

	For Grains							For Vegetables							
Sl No.	t/t_{max}	θ/θ_{max}	U_o/U_{omax}	ρ_s/ρ_f	K_{Exp} (m/s)	K_{Cal} (m/s)	% Dev	t/t_{max}	θ/θ_{max}	U_o/U_{omax}	L/D	K_{Exp} (m/s)	K_{Cal} (m/s)	% Dev
1	0.2	1	1	1152.765	2.89E-03	3.14E-03	-8.70	0.2	1	0.257	1.2	9.47E-04	8.67E-04	8.45
2	0.4	1	1	1152.765	3.95E-03	4.21E-03	-6.79	0.4	1	0.257	1.2	1.43E-03	1.28E-03	10.52
3	0.6	1	1	1152.765	4.57E-03	5.01E-03	-9.67	0.6	1	0.257	1.2	1.93E-03	1.61E-03	15.60
4	0.8	1	1	1152.765	5.01E-03	5.66E-03	-12.88	0.8	1	0.257	1.2	2.20E-03	1.90E-03	13.78
5	1	1	1	1152.765	6.97E-03	6.22E-03	10.74	1	1	0.257	1.2	2.22E-03	2.15E-03	3.09
6	1	0.571	0.757	1152.765	0.003317	3.34E-03	-0.76	1	0.571	0.257	1.2	0.001	9.25E-04	2.03
7	1	0.714	0.757	1152.765	0.004148	3.96E-03	4.56	1	0.714	0.257	1.2	0.001	1.30E-03	-3.16
8	1	0.857	0.757	1152.765	0.004421	4.55E-03	-2.82	1	0.857	0.257	1.2	0.002	1.71E-03	3.85
9	1	1	1	1152.765	0.005614	6.22E-03	-10.86	1	1	0.257	1.2	0.002	2.15E-03	-0.76
10	1	1	0.257	1152.765	0.00231	2.38E-03	-3.01	1	1	0.257	1.2	0.002	2.15E-03	-6.14
11	1	1	0.513	1152.765	0.004033	3.88E-03	3.69	1	1	0.513	0.89	0.003	4.12E-03	-15.93
12	1	1	0.757	1152.765	0.005539	5.11E-03	7.74	1	1	0.757	1.2	0.009	8.94E-03	2.75
13	1	1	1	1152.765	0.00703	6.22E-03	11.48	1	1	1	0.89	0.011	9.93E-03	8.12
14	1	1	0.757	1030.928	0.00424	4.91E-03	-15.85	1	1	1	0.89	0.011	9.93E-03	7.76
15	1	1	0.757	1138.707	0.00451	5.09E-03	-12.79	1	1	1	1.2	0.013	1.29E-02	-2.54
16	1	1	0.757	1152.765	0.00473	5.11E-03	-8.10	1	1	1	1.6	0.019	1.66E-02	14.73
17	1	1	1	1271.79	0.00579	6.45E-03	-11.27	1	1	1	5.2	0.049	4.68E-02	4.29

Table - 24: Physical properties of Red kidney bean at different moisture loss

Time (min)	Moisture Loss	Axial dimension (mm)				Sphericity (%)	Volume (mm^3)	Surface area (mm^2)	Bulk density (kg/m^3)	True density (kg/m^3)	Porosity (%)
		L	W	T	Arithmetic diameter						
10	5.71	17.68	9.12	6.22	11.01	56.45	333.45	201.59	0.130	0.539	75.88
20	7.86	16.53	8.11	5.69	10.11	55.17	251.92	169.76	0.134	0.537	75.05
30	12.06	16.05	8.04	4.68	9.59	52.52	195.16	148.42	0.139	0.533	73.92
40	14	15.53	7.78	4.02	9.11	50.48	155.55	131.01	0.145	0.527	72.48
50	17.25	15.05	7.25	3.75	8.68	49.23	129.33	117.95	0.151	0.523	71.13

Table - 25: Physical properties of Bean seed at different moisture loss

Time (min)	Moisture Loss	Axial dimension (mm)				Sphericity (%)	Volume (mm^3)	Surface area (mm^2)	Bulk density (kg/m^3)	True density (kg/m^3)	Porosity (%)
		L	W	T	Arithmetic diameter						
10	13.5	14.28	8.51	6.63	11.01	65.03	286.42	228.68	739.6	1080.86	0.33
20	17.05	13.55	7.89	5.78	9.07	62.74415	215.82	191.59	778.12	1183.15	0.32
30	22.32	12.98	7.52	5.17	8.56	61.22108	174.26	167.52	816.64	1221.11	0.31
40	27	12.89	7.56	4.92	8.46	60.63591	164.75	161.91	855.16	1301.35	0.29
50	30.17	12.38	7.27	4.72	8.12	60.62793	145.95	149.35	893.68	1424.63	0.27

Table - 26: Physical properties of Wheat at different moisture loss

Time (min)	Moisture Loss	Axial dimension (mm)				Sphericity (%)	Volume (mm^3)	Surface area (mm^2)	Bulk density (kg/m^3)	True density (kg/m^3)	Porosity (%)
		L	W	T	Arithmetic diameter						
10	5.5	7.3	2.84	2.65	4.26	52.006	17.702	38.716	557.33	956.23	0.41
20	8	6.08	2.32	2.27	3.55	52.167	10.327	27.001	595.36	1015.38	0.41
30	9.6	5.22	2.03	2.08	3.11	53.656	7.180	20.967	663.12	1127.71	0.41
40	10.64	4.89	1.85	2.07	2.93	54.252	6.125	18.781	747.24	1207.32	0.38
50	19.2	4.65	1.84	1.89	2.79	54.331	5.292	17.028	785.32	1245.56	0.36

Table - 27: Physical properties of Rice at different moisture loss

Time (min)	Moisture Loss	Axial dimension (mm)				Sphericity (%)	Volume (mm^3)	Surface area (mm^2)	Bulk density (kg/m^3)	True density (kg/m^3)	Porosity (%)
		L	W	T	Arithmetic diameter						
10	8.6	6.89	3.56	2.98	4.47	60.59	25.04	46.13	519.69	1148.89	0.54
20	10	6.85	3.25	2.75	4.28	57.45	20.49	41.12	538.94	1122.73	0.51
30	12.05	6.38	3.12	2.45	3.98	57.19	16.29	35.35	574.43	1087.35	0.47
40	13.25	5.75	2.25	2.32	3.44	53.98	9.80	25.73	593.94	1015.36	0.41
50	14	5.25	2.05	2.07	3.12	53.54	7.25	21.12	615.93	992.29	0.37

Table -28: Comparison of calculated values of efficiencies determined with the physical properties of grains and system parameters of drying against the experimentally observed values of efficiencies.

Sl No.	Samples	Moisture Loss	V (mm^3)	Sa (mm^2)	ϕ (%)	ρ_b (kg/m^3)	ρt (kg/m^3)	ε (%)	$\eta_{Eq-2.9}$	η_1	t/t_{max}	θ/θ_{max}	U_o/U_{omax}	ρ_s/ρ_f	η_2
1	Wheat	5.5	5.293	17.029	54.332	785.32	1245.56	0.370	0.376	0.361	0.2	1	1	1075.914	0.351
2	Wheat	8	6.126	18.782	54.252	747.24	1207.32	0.381	0.325	0.367	0.4	1	0.513	1075.914	0.355
3	Wheat	9.6	7.181	20.967	53.657	663.12	1127.71	0.412	0.326	0.375	0.6	0.8	0.513	895.97	0.360
4	Wheat	10.64	10.328	27.002	52.168	595.36	1015.38	0.414	0.341	0.393	0.8	0.9	0.256	1075.914	0.333
5	Wheat	19.2	17.702	38.716	52.007	557.33	956.23	0.417	0.443	0.414	1	0.8	0.513	1152.765	0.445
6	Rice	8.6	7.252	21.124	53.541	615.93	992.29	0.379	0.381	0.365	1	0.9	0.256	1152.765	0.365
7	Rice	10	9.801	25.739	53.987	593.94	1015.36	0.415	0.411	0.379	0.8	0.9	0.513	1152.765	0.439
8	Rice	12.05	16.291	35.354	57.191	574.43	1087.35	0.472	0.424	0.386	0.6	1	0.513	1152.765	0.419
9	Rice	13.25	20.491	41.126	57.458	538.94	1122.73	0.520	0.429	0.396	1	1	0.256	1152.765	0.391
10	Rice	14	25.047	46.139	60.597	519.69	1148.89	0.548	0.431	0.385	0.8	1	0.513	1075.914	0.469
11	Bean seed	13.5	145.951	149.351	60.628	893.68	1230.07	0.273	0.443	0.447	0.6	0.8	0.756	1012.184	0.421
12	Bean seed	17.05	164.759	161.912	60.636	855.16	1212.76	0.295	0.464	0.458	0.6	0.8	1	1012.184	0.470
13	Bean seed	22.32	174.267	167.528	61.221	816.64	1184.15	0.310	0.471	0.459	0.8	1	0.513	895.97	0.467
14	Bean seed	27	215.821	191.597	62.744	778.12	1154.26	0.326	0.475	0.461	0.8	1	0.513	1012.184	0.468
15	Bean seed	30.17	286.425	228.681	65.029	739.6	1110.43	0.334	0.481	0.459	0.8	1	0.513	1075.914	0.469
16	Red kidney bean	5.71	129.500	149.017	49.230	622	1520	0.591	0.600	0.578	1	0.9	0.756	1152.765	0.560
17	Red kidney bean	7.86	155.003	166.299	50.512	628	1410	0.555	0.535	0.574	1	0.9	0.756	1152.765	0.560
18	Red kidney bean	12.06	195.356	191.085	52.552	696	1340	0.481	0.550	0.568	1	0.9	0.756	1152.765	0.560
19	Red kidney bean	14	251.216	221.887	55.153	769	1300	0.408	0.566	0.553	1	0.9	0.756	1152.765	0.560
20	Red kidney bean	17.25	333.458	265.644	56.486	854	1230	0.306	0.571	0.532	1	0.9	0.7565	1152.765	0.560

Table - 29: Comparisons of calculated values of drying characteristics against the experimentally observed values for grains.

R.A. (for system parameters)						R.A. (physical properties)				
Sl No.	Std. Dev.	Mean Dev.	χ^2	MSE	R^2	Std. Dev.	Mean Dev.	χ^2	MSE	R^2
1	5.53	-0.038	0.023	0.0005	0.953	7.86	0.96	0.045	0.0009	0.924

Table - 30: Physical properties of Ladies finger at different moisture loss

Time (min)	Moisture Loss	Axial dimension (mm)				Sphericity (%)	Volume (mm^3)	Surface area (mm^2)	Bulk density (kg/m^3)	True density (kg/m^3)	Porosity (%)
		L	W	T	Arithmetic diameter						
10	5	54.13	16.03	14.92	28.36	43.24	255.56	1533.39	676.6	760	0.11
20	7.24	52.10	14.15	13.51	26.58	41.17	217.34	1304.07	663.3	700.3	0.05
30	9.57	50.04	12.41	12.16	24.87	39.09	183.45	1100.71	646.6	680.5	0.05
40	12.5	45.7	11.54	12.05	23.09	40.41	161.90	971.41	595.6	615.9	0.03
50	14	43.5	11.29	11.9	22.23	41.28	152.21	913.28	507	557.3	0.09

Table - 31: Physical properties of Ivy gourd (Tundli) at different moisture loss

Time (min)	Moisture Loss	Axial dimension (mm)				Sphericity (%)	Volume (mm^3)	Surface area (mm^2)	Bulk density (kg/m^3)	True density (kg/m^3)	Porosity (%)
		L	W	T	Arithmetic diameter						
10	8	57.26	20.52	18.56	32.11	48.63	352.46	2114.7	843.3	1335	0.37
20	9	56.24	18.85	17.81	30.96	47.19	322.10	1932.65	826.6	1312.9	0.37
30	10.89	54.86	18.13	17.19	30.06	46.81	302.01	1812.08	806.7	1000.8	0.19
40	12.23	50.6	16.85	15.6	27.68	46.67	255.61	1533.69	765.32	956.2	0.20
50	13.5	45.06	13.54	14.59	24.39	45.85	196.34	1178.05	727.24	992.3	0.27

Table - 32: Physical properties of String beans (Barbatti) at different moisture loss

Time (min)	Moisture Loss	Axial dimension (mm)				Sphericity (%)	Volume (mm^3)	Surface area (mm^2)	Bulk density (kg/m^3)	True density (kg/m^3)	Porosity (%)
		L	W	T	Arithmetic diameter						
10	10.87	59.32	5.641	4.983	23.31	19.94	86.14	516.86	303.3	740.8	0.59
20	12.23	57.48	5.332	4.638	22.48	19.51	78.18	469.13	287.9	671.8	0.57
30	14.87	51.7	4.37	3.765	19.94	18.28	57.11	342.68	249	538.9	0.54
40	15	50.24	4.2	3.21	19.21	17.44	50.10	300.60	227	519.6	0.56
50	19.05	47.29	3.74	3	18.01	17.08	42.97	257.82	205	385	0.47

Table - 33: Comparison of calculated values of efficiencies determined with the physical properties of vegetables and system parameters of drying against the experimentally observed values of efficiencies.

Sl No.	Samples	Moisture Loss	V (mm^3)	Sa (mm^2)	ϕ (%)	ρ_b (kg/m^3)	ρt (kg/m^3)	ε (%)	$\eta_{Eq\text{-}2.9}$	η_1	t/t_{max}	θ/θ_{max}	U_o/U_{omax}	ρ_s/ρ_f	η_2
1	Ladies finger	5	86.145	516.867	19.941	303.3	740.8	0.012	0.475	0.461	0.2	0.8	1	360.825	0.472
2	Ladies finger	7.24	78.189	469.134	19.512	287.9	671.8	0.053	0.501	0.499	0.4	0.8	1	929.981	0.492
3	Ladies finger	9.57	57.114	342.684	18.286	249	538.94	0.040	0.503	0.513	0.6	1	1	929.981	0.494
4	Ladies finger	12.5	50.101	300.603	17.442	227	519.69	0.063	0.510	0.526	0.8	0.9	1	929.981	0.528
5	Ladies finger	14	42.971	257.825	17.083	205	385	0.030	0.540	0.527	1	1	1	929.981	0.531
6	Ivy gourd	8	255.566	1533.394	43.240	676.6	760	0.483	0.541	0.563	0.8	0.8	1	929.981	0.543
7	Ivy gourd	9	217.345	1304.072	41.170	663.3	700.3	0.370	0.548	0.567	1	0.9	0.757	929.981	0.554
8	Ivy gourd	10.89	183.453	1100.718	39.098	646.6	680.5	0.194	0.549	0.560	1	1	0.757	522.306	0.560
9	Ivy gourd	12.23	161.902	971.411	40.413	595.6	615.9	0.200	0.562	0.575	0.8	1	0.257	522.306	0.579
10	Ivy gourd	13.5	152.214	913.283	41.289	507	557.3	0.267	0.570	0.589	0.8	0.8	0.513	522.306	0.586
11	String beans	10.87	255.566	2114.781	48.630	843.3	1335	0.891	0.574	0.570	0.8	0.8	0.757	360.825	0.585
12	String beans	12.23	217.345	1932.652	47.192	826.6	1312.9	0.771	0.594	0.575	1	0.8	1	360.825	0.594
13	String beans	14.87	183.453	1812.081	46.807	806.7	1000.89	0.638	0.600	0.591	1	0.8	1	360.825	0.594
14	String beans	15	161.902	1533.699	46.677	765.32	956.23	0.763	0.630	0.607	1	0.8	0.513	522.306	0.605
15	String beans	19.05	152.214	1178.054	45.854	727.24	992.29	0.968	0.635	0.617	1	0.8	0.256	929.981	0.609

Table - 34: Comparisons of calculated values of drying characteristics against the experimentally observed values for vegetables.

	R.A. (for system parameters)					R.A. (physical properties)				
Sl No.	Std. Dev.	Mean Dev.	χ^2	MSE	R^2	Std. Dev.	Mean Dev.	χ^2	MSE	R^2
1	5.84	-0.13	0.066	0.007	0.98	14.7	-1.24	0.29	0.026	0. 95

Table - 35: L16 orthogonal array response values and S/N ratio on moisture loss for grains.

Trail No.	t (min)	θ (^oC)	U_o (m/s)	Red kidney bean	Bean	Wheat	Rice		
				M_L	M_L	M_L	M_L	S/N ratio	STDEV
1	10	40	0.95	0.440	0.29	0.280	0.290	9.584	0.077
2	10	50	1.95	0.230	0.27	0.260	0.250	11.940	0.017
3	10	60	2.80	0.220	0.26	0.200	0.150	13.504	0.046
4	10	70	3.80	0.150	0.22	0.160	0.130	15.475	0.039
5	20	40	1.95	0.410	0.25	0.200	0.150	11.350	0.113
6	20	50	0.95	0.210	0.20	0.160	0.140	14.905	0.033
7	20	60	3.80	0.066	0.14	0.150	0.100	18.504	0.039
8	20	70	2.80	0.140	0.12	0.066	0.076	19.573	0.035
9	30	40	2.80	0.089	0.11	0.200	0.130	17.160	0.048
10	30	50	3.80	0.065	0.10	0.091	0.120	20.350	0.023
11	30	60	0.95	0.036	0.09	0.064	0.053	23.899	0.023
12	30	70	1.95	0.093	0.05	0.042	0.020	24.778	0.031
13	40	40	3.80	0.052	0.07	0.057	0.067	24.162	0.008
14	40	50	2.80	0.048	0.06	0.034	0.066	26.480	0.024
15	40	60	1.95	0.033	0.04	0.033	0.052	27.904	0.009
16	40	70	0.95	0.016	0.02	0.028	0.047	28.189	0.013

Table - 36: L16 orthogonal array response values and S/N ratio on moisture loss for vegetables.

Trail No.	T (min)	θ (^oC)	U_o (m/s)	Mushroom	String bean	Ladies finger	Ivy gourd	Radish		
				M_L	M_L	M_L	M_L	M_L	S/N ratio	STDEV
1	10	40	0.95	0.09	0.16	0.12	0.050	0.06	18.81	0.056
2	10	50	1.95	0.07	0.17	0.09	0.033	0.09	19.97	0.041
3	10	60	2.80	0.11	0.21	0.19	0.069	0.10	20.65	0.038
4	10	70	3.80	0.09	0.24	0.17	0.071	0.12	21.74	0.032
5	20	40	1.95	0.06	0.28	0.15	0.043	0.04	19.42	0.054
6	20	50	0.95	0.05	0.30	0.12	0.037	0.02	19.52	0.052
7	20	60	3.80	0.10	0.25	0.20	0.150	0.09	19.65	0.045
8	20	70	2.80	0.08	0.29	0.18	0.130	0.05	19.90	0.050
9	30	40	2.80	0.04	0.31	0.14	0.083	0.02	16.69	0.061
10	30	50	3.80	0.03	0.32	0.12	0.062	0.01	16.41	0.068
11	30	60	0.95	0.09	0.16	0.12	0.050	0.06	16.65	0.103
12	30	70	1.95	0.07	0.17	0.09	0.033	0.09	16.62	0.115
13	40	40	3.80	0.11	0.21	0.19	0.069	0.10	15.43	0.068
14	40	50	2.80	0.09	0.24	0.17	0.071	0.12	15.45	0.094
15	40	60	1.95	0.06	0.28	0.15	0.043	0.04	16.03	0.116
16	40	70	0.95	0.05	0.30	0.12	0.037	0.02	16.13	0.125

Table - 37: L16orthogonal array response values and S/N ratio on diffusivity for vegetables.

Trail No.	T (min)	θ (^oC)	U_o (m/s)	Mushroom	String bean	Ladies finger	Ivy gourd	Radish		
				$D_{eff.}$ (m^2/s)	$D_{eff.}$ (m^2/s)	$D_{eff.}$ (m^2/s)	$D_{eff.}$ (m^2/s)	$D_{eff.}$ (m^2/s)	S/N ratio	STDEV
1	10	40	0.95	0.009	9E-05	6E-04	0.004	5E-05	5E-05	47.105
2	10	50	1.95	0.005	6E-05	2E-04	0.001	5E-05	5E-05	52.832
3	10	60	2.80	0.001	4E-05	8E-05	2E-05	4E-05	4E-05	66.946
4	10	70	3.80	8E-04	1E-05	5E-05	1E-05	2E-05	2E-05	68.907
5	20	40	1.95	0.007	8E-06	0.004	0.007	4E-06	4E-06	46.421
6	20	50	0.95	0.005	6E-06	0.001	0.005	1E-05	1E-05	49.914
7	20	60	3.80	0.002	2E-06	5E-04	1E-04	7E-06	7E-06	60.696
8	20	70	2.80	9E-04	1E-06	1E-04	2E-05	6E-06	6E-06	67.849
9	30	40	2.80	0.008	4E-05	8E-04	5E-04	0.0001	0.0001	48.867
10	30	50	3.80	0.004	1E-05	4E-04	3E-04	9E-05	9E-05	54.879
11	30	60	0.95	9E-04	6E-06	2E-05	2E-05	6E-05	6E-05	67.881
12	30	70	1.95	7E-04	5E-06	9E-06	1E-05	5E-05	5E-05	70.064
13	40	40	3.80	0.005	3E-05	5E-04	0.001	8E-05	8E-05	52.797
14	40	50	2.80	0.001	9E-06	1E-04	4E-04	6E-05	6E-05	66.294
15	40	60	1.95	8E-04	4E-06	9E-05	2E-04	2E-05	2E-05	68.611
16	40	70	0.95	6E-04	2E-06	4E-05	1E-04	1E-05	1E-05	71.288

Table - 38: L16 orthogonal array response values and S/N ratio on efficiency for vegetables.

Trail No.	T (min)	θ (^oC)	U_o (m/s)	Mushroom	String beans	Ladies finger	Ivy gourd	Radish		
				η	η	η	η	η	S/N ratio	STDEV
1	10	40	0.95	0.971	0.954	0.997	0.094	0.923	-0.55	0.122
2	10	50	1.95	0.944	0.940	0.947	0.09	0.747	1.104	0.431
3	10	60	2.80	0.921	0.801	0.941	0.844	0.669	1.161	0.146
4	10	70	3.80	0.875	0.771	0.916	0.793	0.666	1.842	0.097
5	20	40	1.95	0.888	0.708	0.911	0.763	0.621	2.094	0.122
6	20	50	0.95	0.766	0.627	0.807	0.595	0.369	3.725	0.173
7	20	60	3.80	0.723	0.528	0.826	0.487	0.377	4.285	0.182
8	20	70	2.80	0.638	0.525	0.72	0.38	0.338	5.347	0.163
9	30	40	2.80	0.674	0.441	0.712	0.282	0.333	5.693	0.196
10	30	50	3.80	0.579	0.354	0.719	0.279	0.264	6.477	0.201
11	30	60	0.95	0.441	0.340	0.71	0.221	0.201	7.432	0.207
12	30	70	1.95	0.436	0.205	0.605	0.23	0.200	8.602	0.180
13	40	40	3.80	0.393	0.293	0.553	0.232	0.185	8.967	0.146
14	40	50	2.80	0.311	0.237	0.528	0.223	0.183	9.870	0.137
15	40	60	1.95	0.267	0.282	0.471	0.191	0.156	10.615	0.122
16	40	70	0.95	0.293	0.189	0.465	0.149	0.124	11.244	0.139

Table - 39: Analysis of variance (ANOVA) of factors affecting in drying process on moisture loss for grains

Source	DOF	SS	MS	F-ratio	Confidence/Percentage (%) (SS/SS_{Total}) *100	P< 0.05
Time	3	0.0871	0.029	19.25	0.726	0.000
Temperature	3	0.026	0.00851	4.07	0.213	0.001
Velocity	3	0.0052	0.00172	1.61	0.043	0.05
Residual Error	6	0.00223	0.00037			
Total	15	0.1200				

Table - 40: Analysis of variance (ANOVA) of factors affecting in drying process on moisture loss for vegetables

Source	DOF	SS	MS	F-ratio	Confidence/Percentage (%) (SS/SS_{Total}) *100	P< 0.05
Time	3	0.00542	0.0018	45.39	0.661	0.000
Temperature	3	0.00197	.000657	16.50	0.240	0.003
Velocity	3	0.00057	0.00019	4.76	0.069	0.05
Residual Error	6	0.00024	0.00040			
Total	15	0. 0082				

Table - 41: Analysis of variance (ANOVA) of factors affecting in drying process on diffusivity for vegetables

Source	DOF	SS	MS	F-ratio	Confidence/Percentage (%) (SS/SS_{Total}) *100	P< 0.05
Time	3	0.000003	0.000001	9.48	0.167	0.011
Temperature	3	0.000013	0.00004	42.69	0.722	0.000
Velocity	3	0.000002	0.000001	5.18	0.111	0.042
Residual Error	6	0.000001	0.000000			
Total	15	0. 000018				

Table - 42: Analysis of variance (ANOVA) of factors affecting in drying process on efficiency for vegetables

Source	DOF	SS	MS	F-ratio	Confidence/Percentage (%) (SS/SS_{Total}) *100	P< 0.05
Time	3	0.817	0.272	88.94	0.892	0.000
Temperature	3	0.0768	0.026	8.36	0.084	0.015
Velocity	3	0.0042	0.0014	0.45	0.005	0.024
Residual Error	6	0.0184	0.0031			
Total	15	0. 916				

Table -43: Estimated model coefficients by Taguchi Analysis on moisture loss for grains

Term	Coefficient	SE coefficient	T	P
Constant	0.132094	0.004838	0.000	0.000
Time	0.105406	0.008379	12.580	0.000
Time	0.029031	0.008379	3.465	0.013
Time	-0.047531	0.008379	-5.673	0.001
Temperature	0.060719	0.008379	7.247	0.000
Temperature	0.009531	0.008379	1.138	0.029
Temperature	-0.026656	0.008379	-3.181	0.019
Velocity	0.018031	0.008379	2.152	0.045
Velocity	0.016844	0.008379	2.010	0.051
Velocity	-0.011406	0.008379	-1.361	0.022
S = 0.01935	R-Sq = 98.1%	R-Sq(adj) = 95.3%		

Table - 44: Estimated model coefficients by Taguchi Analysis on moisture loss for vegetables

Term	Coefficient	SE coefficient	T	P
Constant	0.110075	0.001577	69.781	0.000
Time	-0.020225	0.002732	-7.402	0.000
Time	-0.015875	0.002732	-5.810	0.001
Time	0.013425	0.002732	4.914	0.003
Temperature	0.013025	0.002732	4.767	0.003
Temperature	0.008025	0.002732	2.937	0.026
Temperature	-0.006225	0.002732	-2.278	0.063
Velocity	-0.004825	0.002732	-1.766	0.028
Velocity	-0.006875	0.002732	-2.516	0.046
Velocity	0.004575	0.002732	1.674	0.045
S = 0.06310	R-Sq = 97.1%	R-Sq(adj) = 92.7%		

Table - 45: Estimated model coefficients by Taguchi Analysis on diffusivity for vegetables

Term	Coefficient	SE coefficient	T	P
Constant	0.001011	0.000078	12.892	0.000
Time	0.000095	0.000136	0.703	0.05
Time	0.000623	0.000136	4.585	0.004
Time	-0.000210	0.000136	-1.544	0.07
Temperature	0.001379	0.000136	10.160	0.000
Temperature	0.000174	0.000136	1.283	0.047
Temperature	-0.000715	0.000136	-5.267	0.002
Velocity	0.000315	0.000136	2.321	0.05
Velocity	0.000300	0.000136	2.209	0.06
Velocity	-0.000350	0.000136	-2.576	0.042
S = 0.0003136	R-Sq = 96.6%	R-Sq(adj) = 91.6%		

Table - 46: Estimated model coefficients by Taguchi Analysis on efficiency for vegetables

Term	Coefficient	SE coefficient	T	P
Constant	0.551928	0.01383	39.906	0.000
Time	0.328281	0.02396	13.704	0.000
Time	0.077933	0.02396	3.253	0.017
Time	-0.140629	0.02396	-5.870	0.001
Temperature	0.112546	0.02396	4.698	0.003
Temperature	-0.011958	0.02396	-0.499	0.06
Temperature	-0.024515	0.02396	-1.023	0.046
Velocity	0.027871	0.02396	1.163	0.08
Velocity	-0.007384	0.02396	-0.308	0.06
Velocity	-0.009276	0.02396	-0.387	0.012
S = 0.05532	R-Sq = 98.0%	R-Sq(adj) = 95.0%		

Appendix III

Weights of ANN Learning

Table - 1

For moisture content of grains:

Weight of training dataset - 1

25000 - CYCLES

input to hidden layer weights

w1[0][1] = 1.164237 w1[0][2] = 1.311587 w1[1][1] = -0.061339 w1[1][2] = 0.061748

w1[2][1] = 0.017071 w1[2][2] = -0.003300 w1[3][1] = -0.029836 w1[3][2] = 0.079192

w1[4][1] = 0.064568 w1[4][2] = 0.049321 w1[5][1] = 0.000000 w1[5][2] = 0.00000

hidden layer to o/p layer weights

w2[0][0] = -2.004973 w2[0][1] = -1.899719 w2[0][2] = -1.899152 w2[0][3] = -1.945219 w2[0][4] = -0.320941 w2[0][5] = -2.015513 w2[1][0] = -1.200505 w2[1][1] = -1.156764 w2[1][2] = -1.181803 w2[1][3] = -1.182261 w2[1][4] = -0.051269 w2[1][5] = -1.117270 w2[2][0] = -1.247911 w2[2][1] = -1.283708 w2[2][2] = -1.266858 w2[2][3] = -1.194886 w2[2][4] = -0.150672 w2[2][5] = -1.148192

Table - 2

For moisture content of vegetables:

Weight of training dataset - 2

20000 – CYCLES

input to hidden layer weights

w1[0][1] = 0.795117 w1[0][2] = 0.916524 w1[1][1] = 0.676824 w1[1][2] = 0.801690 w1[2][1] = 0.022667 w1[2][2] = 0.001685 w1[3][1] = -0.025124 w1[3][2] = 0.083367 w1[4][1] = 0.069878 w1[4][2] = 0.055329 w1[5][1] = 0.000000 w1[5][2] = 0.000000

hidden layer to o/p layer weights

w2[0][0] = -1.666777 w2[0][1] = -1.613919 w2[0][2] = -1.612782 w2[0][3] = -1.670750 w2[0][4] = 0.403675 w2[0][5] = -1.685609 w2[1][0] = -1.031415 w2[1][1] = -1.024588 w2[1][2] = -1.048517 w2[1][3] = -1.062183 w2[1][4] = 0.350977 w2[1][5] = -0.952796 w2[2][0] = -1.113013 w2[2][1] = -1.187858 w2[2][2] = -1.165938 w2[2][3] = -1.109729 w2[2][4] = 0.288314 w2[2][5] = -1.009341

Table - 3

For diffusivity of mushroom:

Weight of training dataset - 3

20000 - CYCLES

input to hidden layer weights

w1[0][1] = 350.567505 w1[0][2] = 200.497620 w1[1][1] = -0.048575 w1[1][2] = 0.068990 w1[2][1] = 39.730114 w1[2][2] = 22.686586 w1[3][1] = 226.705704 w1[3][2] = 129.695084 w1[4][1] = 17.358318 w1[4][2] = 9.933708 w1[5][1] = 0.000000 w1[5][2] = 0.000000

hidden layer to o/p layer weights

w2[0][0] = -4.357804 w2[0][1] = -6.895851 w2[0][2] = -2.932073 w2[0][3]=-7.791589 w2[0][4] = 121902480.000000 w2[0][5] = -0.591789 w2[1][0] = -4.374531 w2[1][1] = -6.995813 w2[1][2] = -3.041407 w2[1][3] = -7.862414 w2[1][4] = 121902480.00000 w2[1][5] = -0.506408 w2[2][0] = -4.368929 w2[2][1] = -7.068745 w2[2][2] = -3.068040 w2[2][3] = -7.819252 w2[2][4] = 121902480.000000 w2[2][5] = -0.478302

Table - 4

For diffusivity of vegetables:

Weight of training dataset - 4

20000 – CYCLES

input to hidden layer weights

w1[0][1] = 2.019238 w1[0][2] = 2.074821 w1[1][1] = -0.061339 w1[1][2] = 0.061748 w1[2][1] = 1.228194 w1[2][2] = 1.175717 w1[3][1] = 1.424996w1[3][2] = 1.495038 w1[4][1] = 0.16384 w1[4][2] = 0.146140 w1[5][1] = 0.000000 w1[5][2] = 0.000000

hidden layer to o/p layer weights

w2[0][0] = -4.203183 w2[0][1] = -2.806844 w2[0][2] = -2.006096 w2[0][3] = -6.592771 w2[0][4] = -1.314862 w2[0][5] = -0.755826 w2[1][0] = -3.338596 w2[1][1] = -2.231783 w2[1][2] = -1.566668 w2[1][3] = -5.466899 w2[1][4] = -0.752985 w2[1][5] = -0.413776 w2[2][0] = -3.432730 w2[2][1] = -2.387677 w2[2][2] = -1.659867 w2[2][3] = -5.578706 w2[2][4] = -0.894421 w2[2][5] = -0.418615

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List of Publications

Journals Published

- Subasini Jena, Abanti Sahoo, "ANN modeling for diffusivity of mushroom and vegetables using a fluidized bed dryer". Particuology, 11, 2013, 607– 613.

Journals Communicated

- Subasini Jena, Abanti Sahoo, "Studies on the Effects of Physical Properties of Feed Samples on the Performance of Fluidized Bed Dryer". Communicated in Particulate Science.
- Subasini Jena, Abanti Sahoo, "Studies on Moisture Loss with Shrinkage of Food Grains and Vegetables for Transfer Coefficients Using a Fluidized Bed Dryer". Communicated in Journal of Food Engineering.
- Subasini Jena, Abanti Sahoo, "Studies on Mass Transfer Aspects for Different Crops Using a Fluidized Bed Dryer". Communicated in Asia-Pacific Journal of Chemical Engineering.

Conference Proceeding

- Subasini Jena, Abanti Sahoo, "A Comparative Study on Drying Kinetics of Different Vegetables, Grains and Mushrooms Dried in a Fluidized Bed Dryer: ANN approach". International Journal of Systems, Algorithms & Applications, 2, 2012, P.81-84.
- Jena S, Sahoo A, "Effects of Physical Properties on Fluidized bed Drying of Wheat". 978-1-4673-6150-7/13/$31.00 ©2013 IEEE.
- S. Jena and A. Sahoo. "Studies on Moisture Content of Food Grains and Vegetables Dried in a Fluidized Bed Dryer: ANN Approach". 31st National Convention of Chemical

Engineers & National Seminar on: “TECHNOLOGICAL ADVANCEMENT IN CHEMICAL ENGINEERING AND MINERAL PROCESSING”, 2015, P. 10-15.